Bridging Scales in Global Climate System Modeling

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Ocean Model: Doug Jacobsen, Mark Petersen, Mat Maltrud, Phil Jones, Qingshan Chen

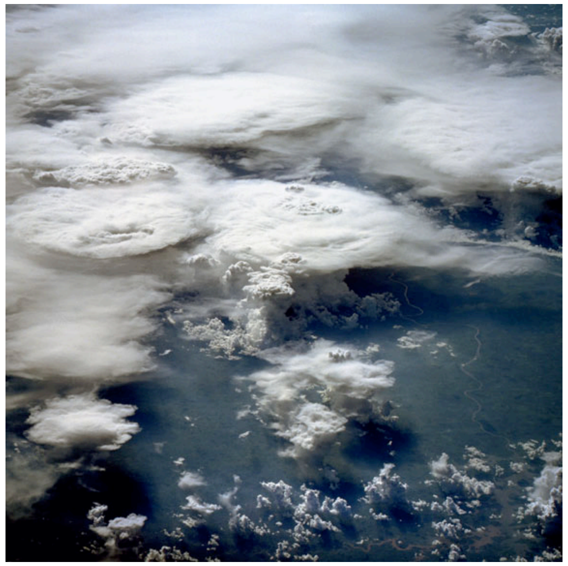
Atmosphere Model: Michael Duda, Bill Skamarock, Joe Klemp, Sara Rauscher

Grid Generation: Lili Ju, Max Gunzburger

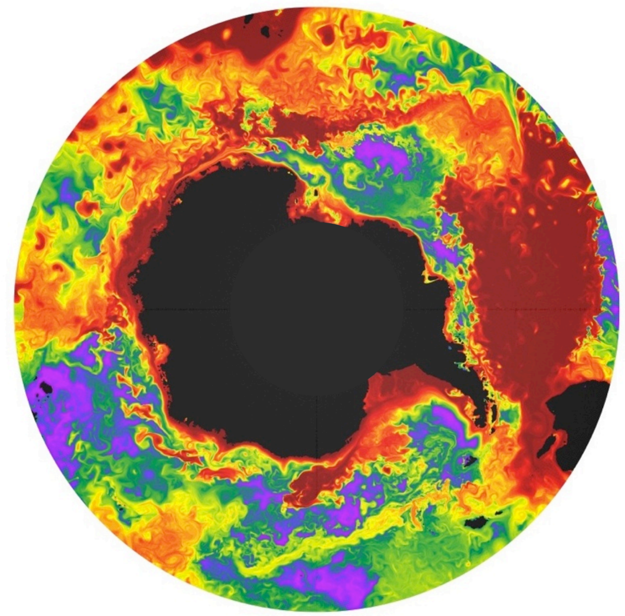
Shared Framework: All of the above!

Underpinning Premise: Presently unresolved scales are likely important to our understanding of global climate change.

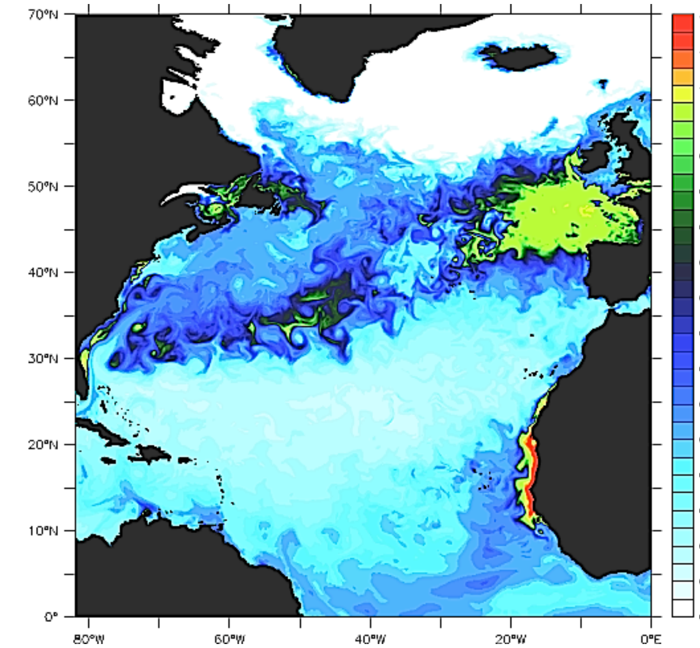
Cloud Processes



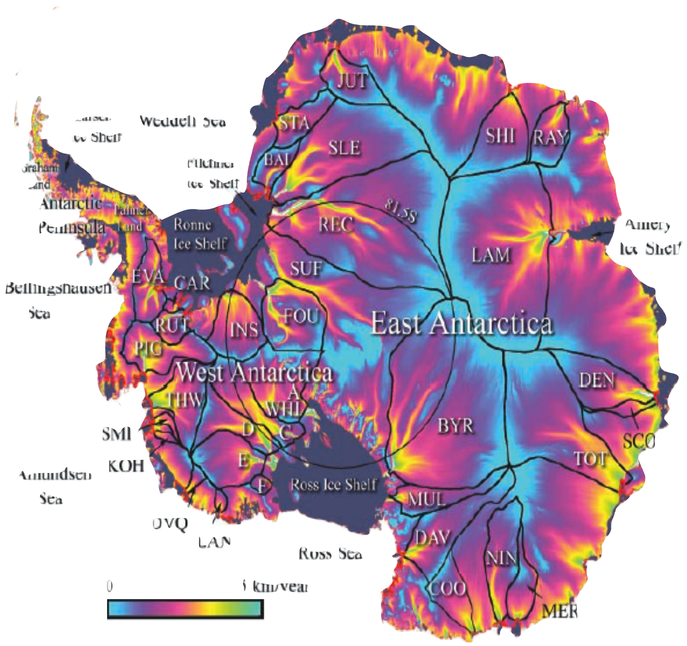
Ocean/Atmosphere Interaction



Ocean Biogeochemistry



Ocean/Ice Shelf Interaction

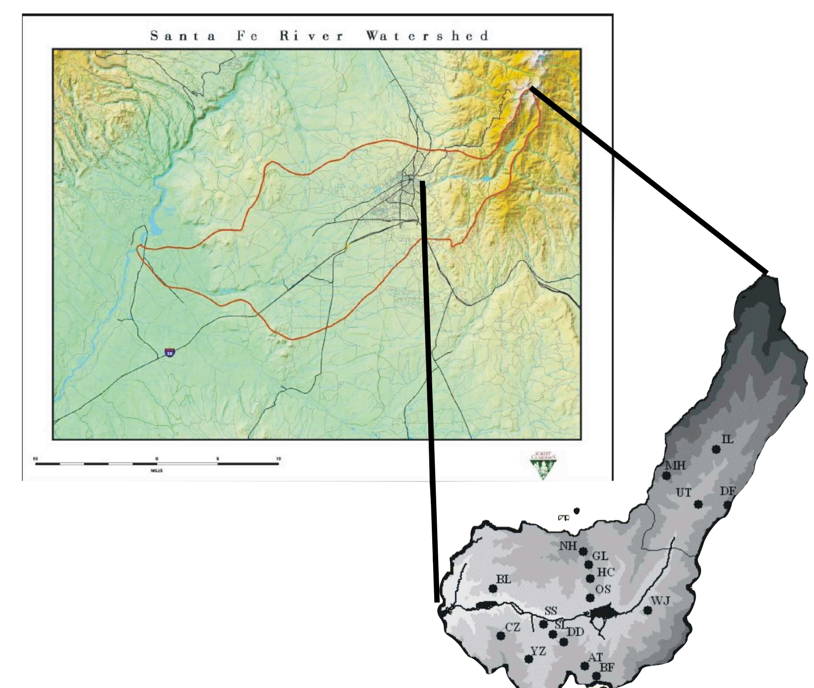


Each of these examples demonstrate scale-sensitive processes that might impact the climate system in a fundamental and important way.

The scale of these processes is O(km).

Studying these processes within the context of a global, quasi-uniform Earth modeling system is nearly impossible.

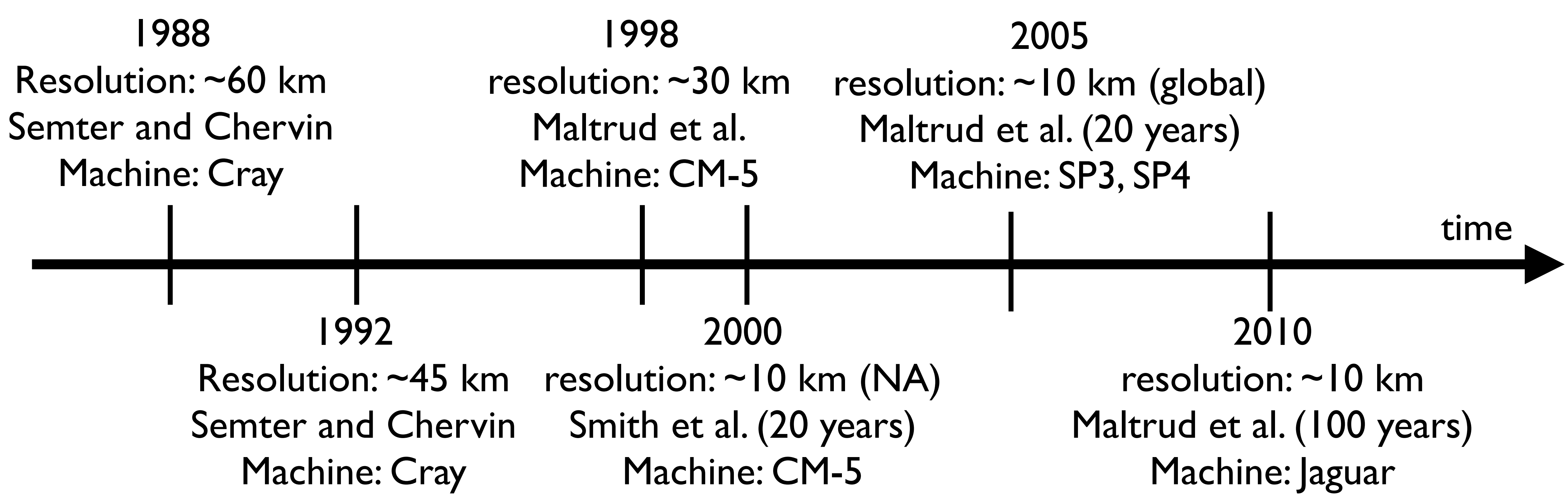
Hydrology in Complex Terrain



Summary of the Current Approach to Global Climate Modeling

Typical Workflow:

1. Optimize for new computer system
2. Allocate addition computing power
   a. to increased complexity
   b. to increased resolution for each component
3. Conduct new suite of simulations
   a. do science
   b. identify biases and deficiencies
4. Return to 1.



Current Approach to Global Climate Modeling: Strengths

1. Experience: For example, the basic structure of our global ocean model was put into place in 1969 by Kirk Bryan.[1]

2. Equitable in terms of temporal/spatial scales: With quasi-uniform meshes we have a clear distinction between what is resolved and what is not resolved.

3. Mitigates deficiencies in physical parameterizations: We know that our parameterizations of unresolved scales are incomplete and sometimes very sensitive tc our spatial and temporal truncation scale.

Parallel Ocean Program
tri-pole, stretched grid

1. Bryan, K. (1969). A numerical method for the study of the circulation of the world ocean. *Journal of Computational Physics*: This contribution used realistic bathymetry and coastlines, z-level coordinates, energy-conserving numerics, structured meshes, non-linear equation of state and a treatment of the external, barotropic mode.

Current Approach to Global Climate Modeling: Weaknesses

1. Rate of reduction in structural uncertainty: Scoping the importance of unresolved processes is difficult in the current paradigm.

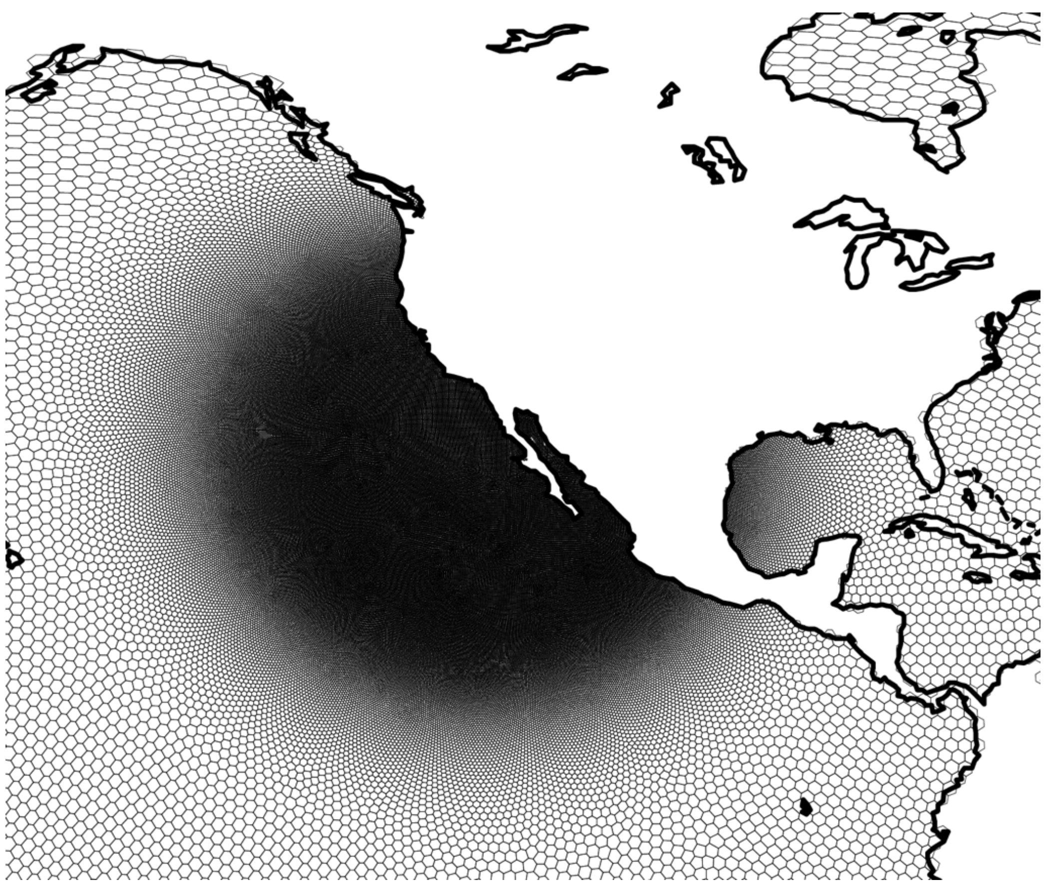
2. Rate of transition from parameterization to direct simulation: A basic tenet of global climate simulation is the our simulations are more robust as we transition from parameterization to direct simulation. This transition is very slow with the global, quasi-uniform approach.

3. Pushing the boundary of resolution is limited to a relatively small number of scientists with special expertise, access to a small number of big machines and the energy to conduct grand-challenge simulations.

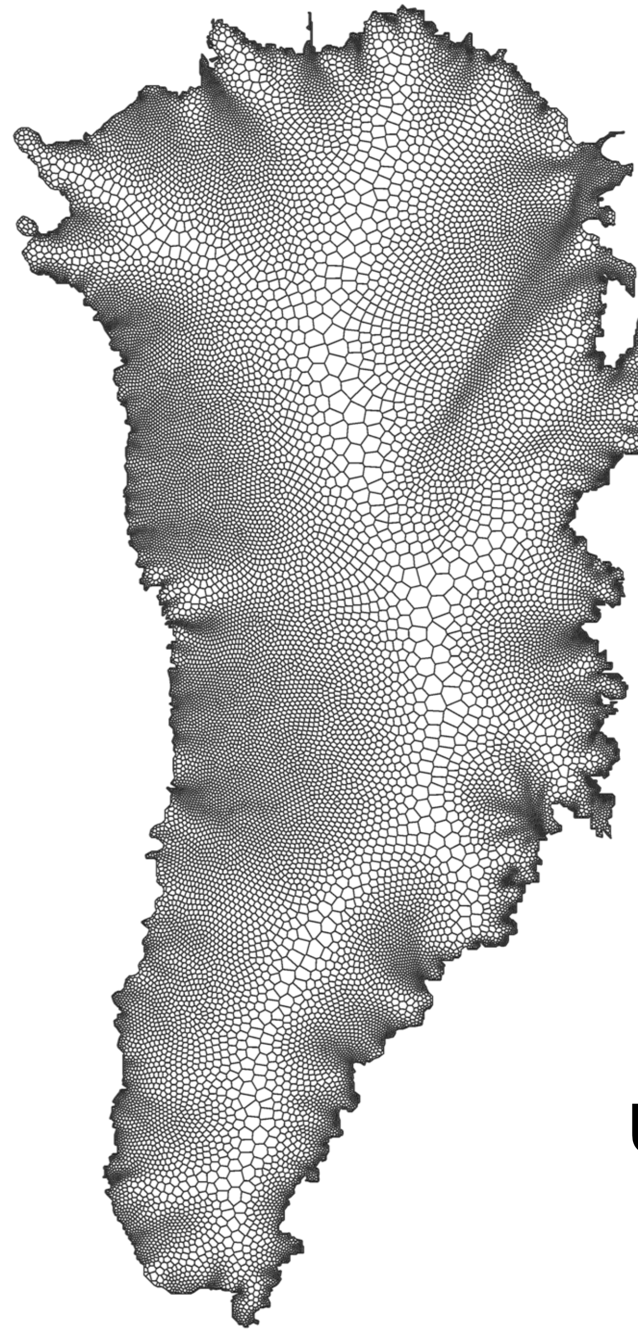
The equitable partitioning of incremental increases in computer resources leads a very solid, but a relatively slowly evolving, approach to global climate simulation.

There has got to be a better way.

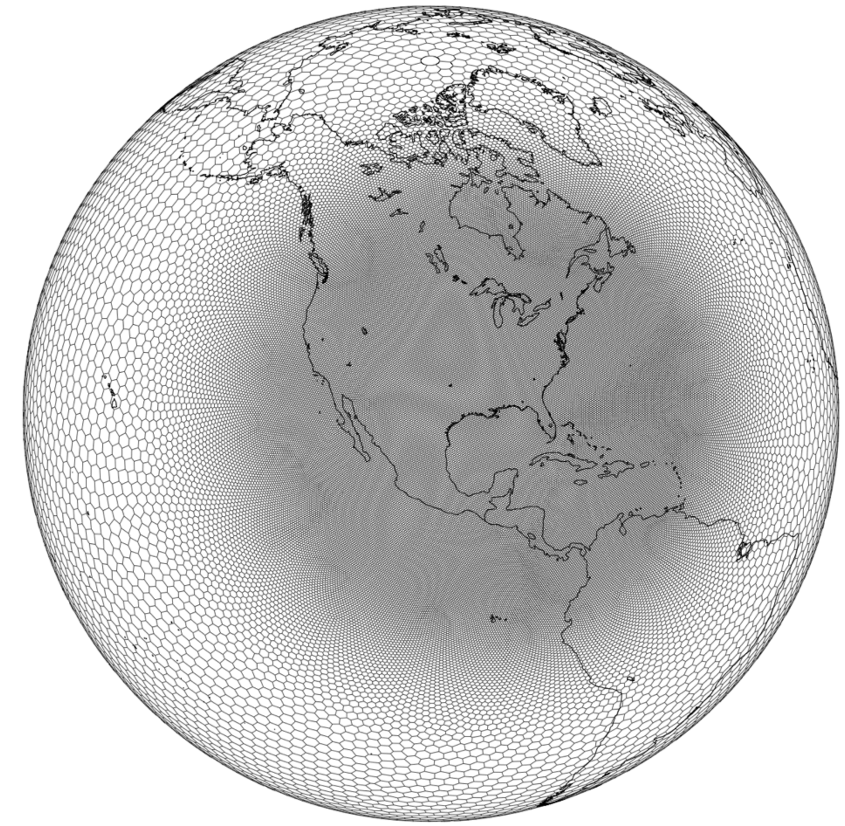
An alternative approach is to distribute computational resources based on the scientific question(s) being asked.



Increased resolution off west coast of North America to study the California Current. (LANL)

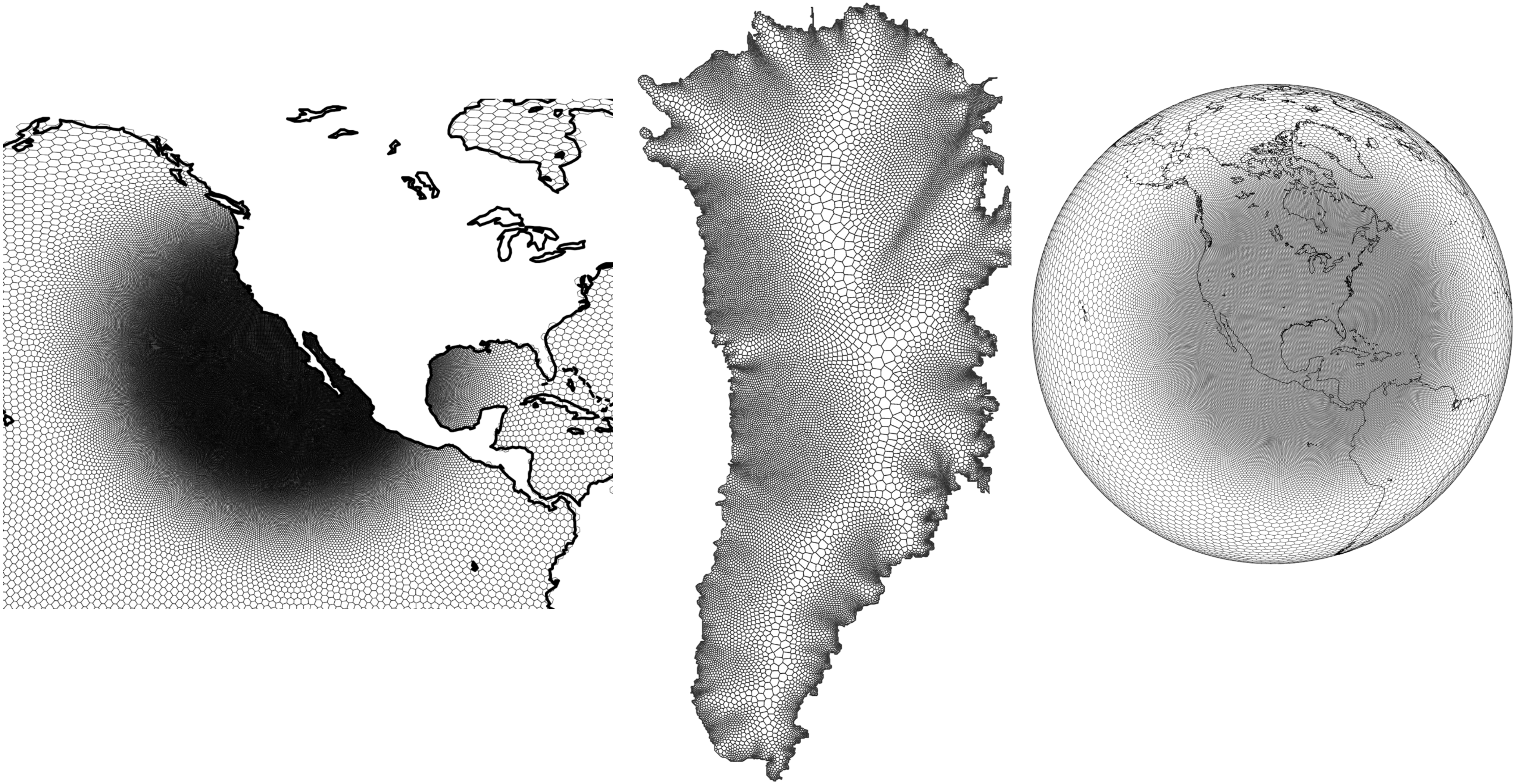


Increased resolution in regions of fast ice flow to better simulate ice dynamics. (FSU / LANL)



Increased resolution over United States to study regional impacts of climate change. (NCAR/MMM)

An alternative approach is to distribute computational resources based on the scientific question(s) being asked.



At the end of the talk, I will come back to why this multi-resolution approach is a valuable addition to global modeling, but first I want to convince you that it is possible.

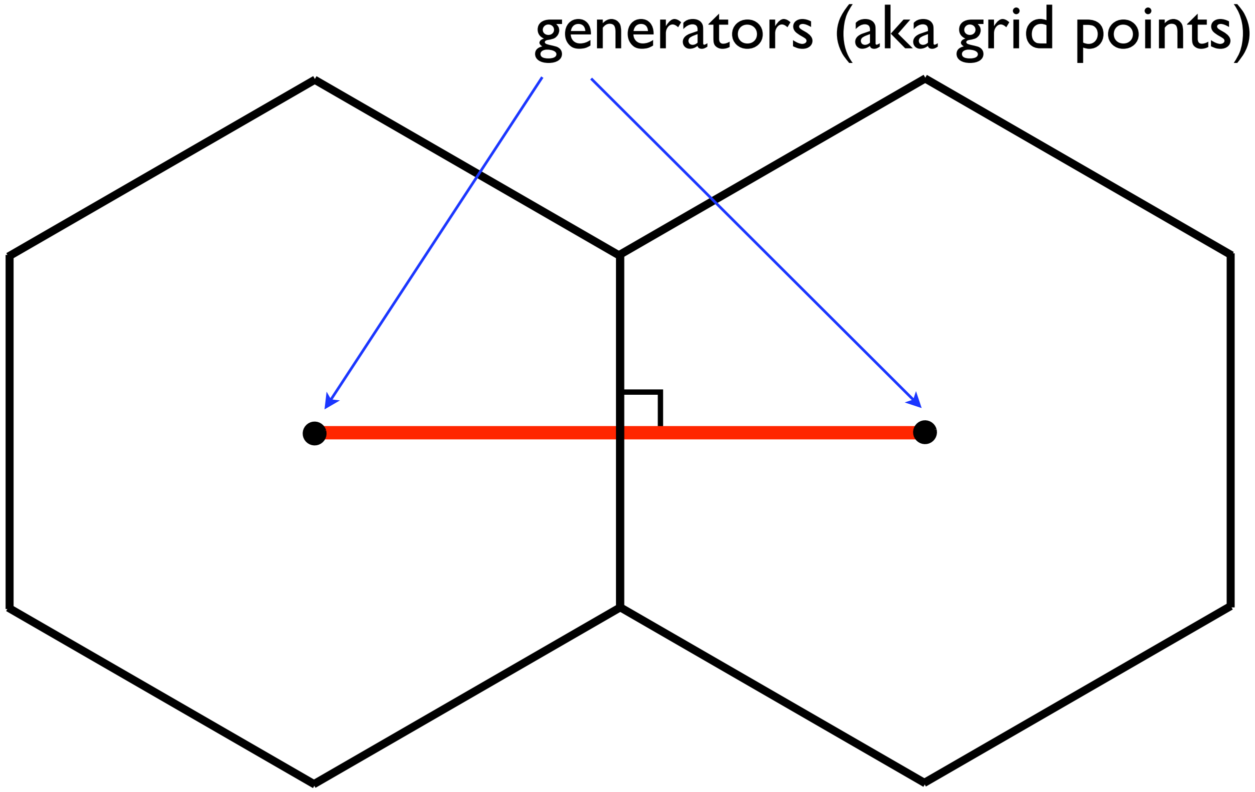
Spherical **C**entroidal **V**oronoi **T**essellation (SCVT):
A way to build robust, global, multi-resolution conforming meshes.

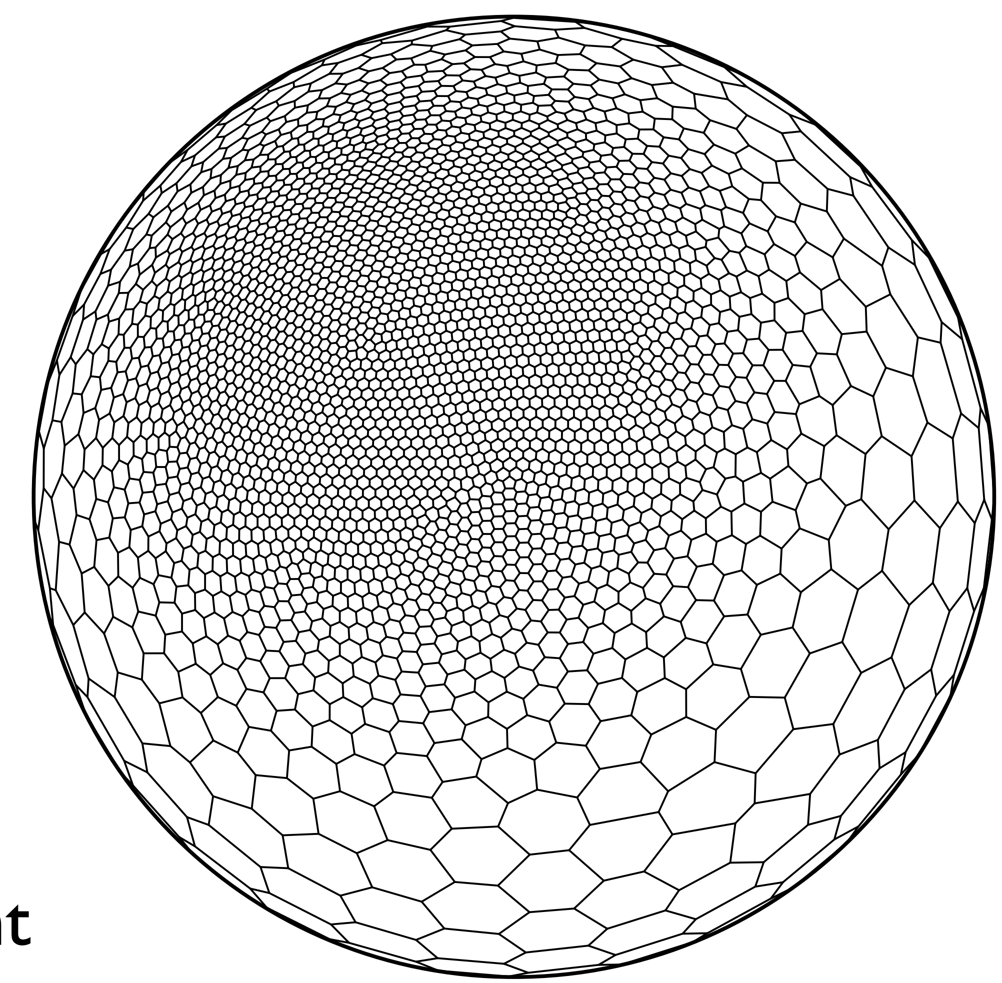
Spherical: The two-dimensional surface to be tessellated.

Centroidal: The magic ingredient that makes it all possible.

Voronoi: The type of tiling.

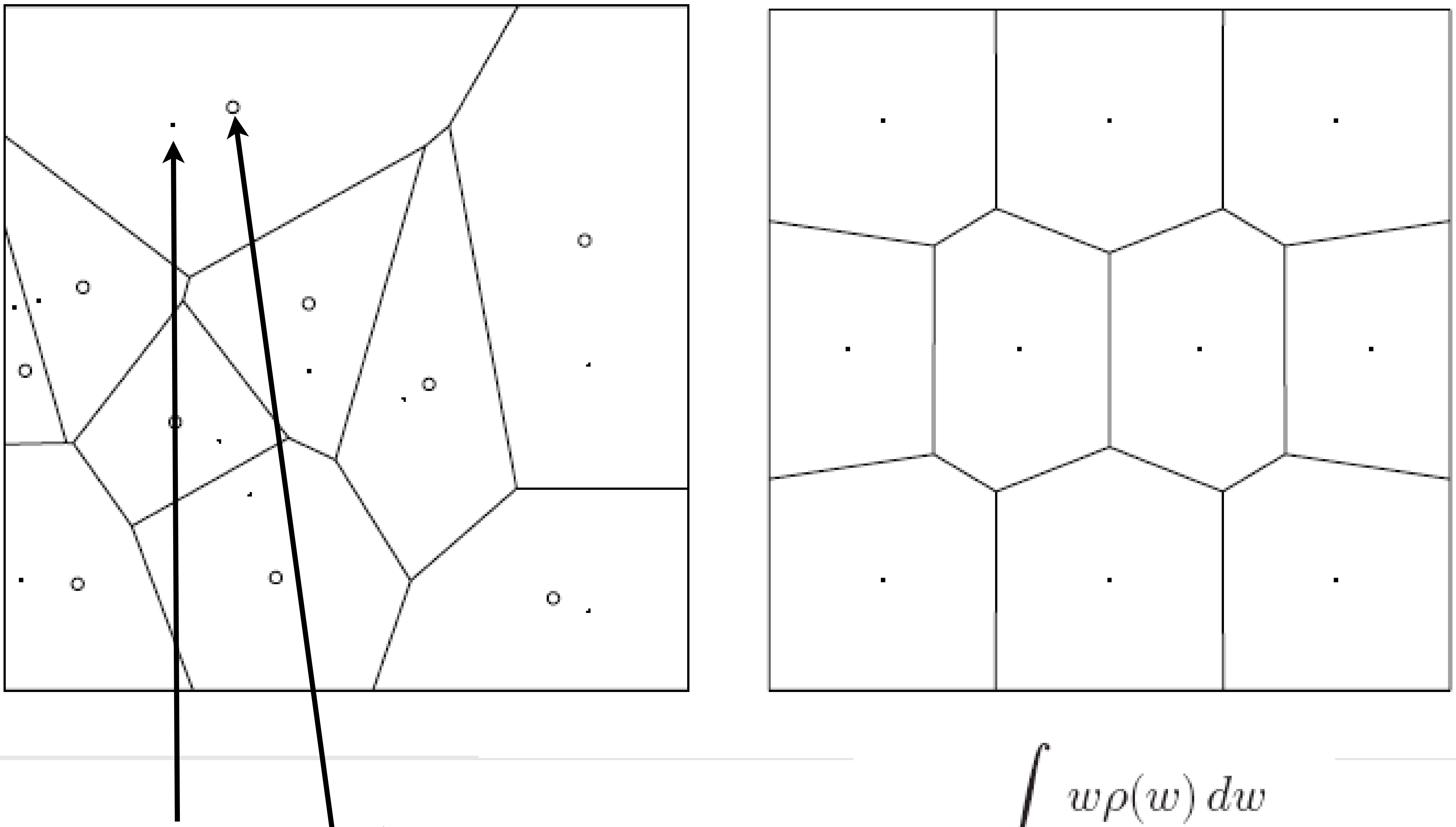
Tessellation: A non-overlapping tiling of two dimensions.





What makes a mesh a Voronoi mesh? Every point in domain is assigned to the closest generator.

Spherical **C**entroidal **V**oronoi **T**essellation (SCVT):
A way to build robust, global, multi-resolution conforming meshes.

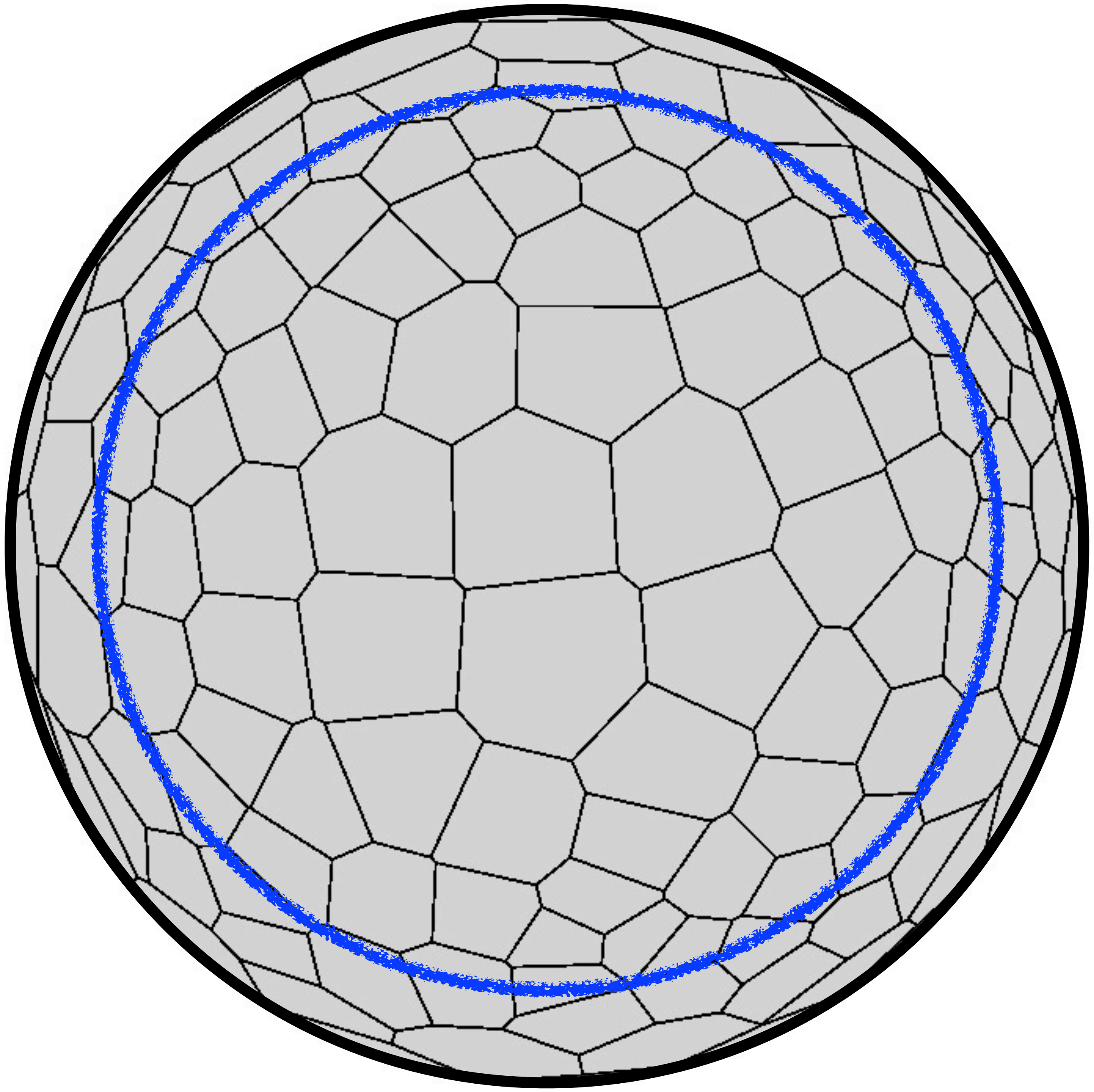


z_i

z_i^* = center of mass wrt
a **user-defined** density function

$$z^* = \frac{\int_V w\rho(w)\,dw}{\int_V \rho(w)\,dw}$$

Making the mesh ....



As far as mesh generation goes, SCVTs have a strong mathematical foundation

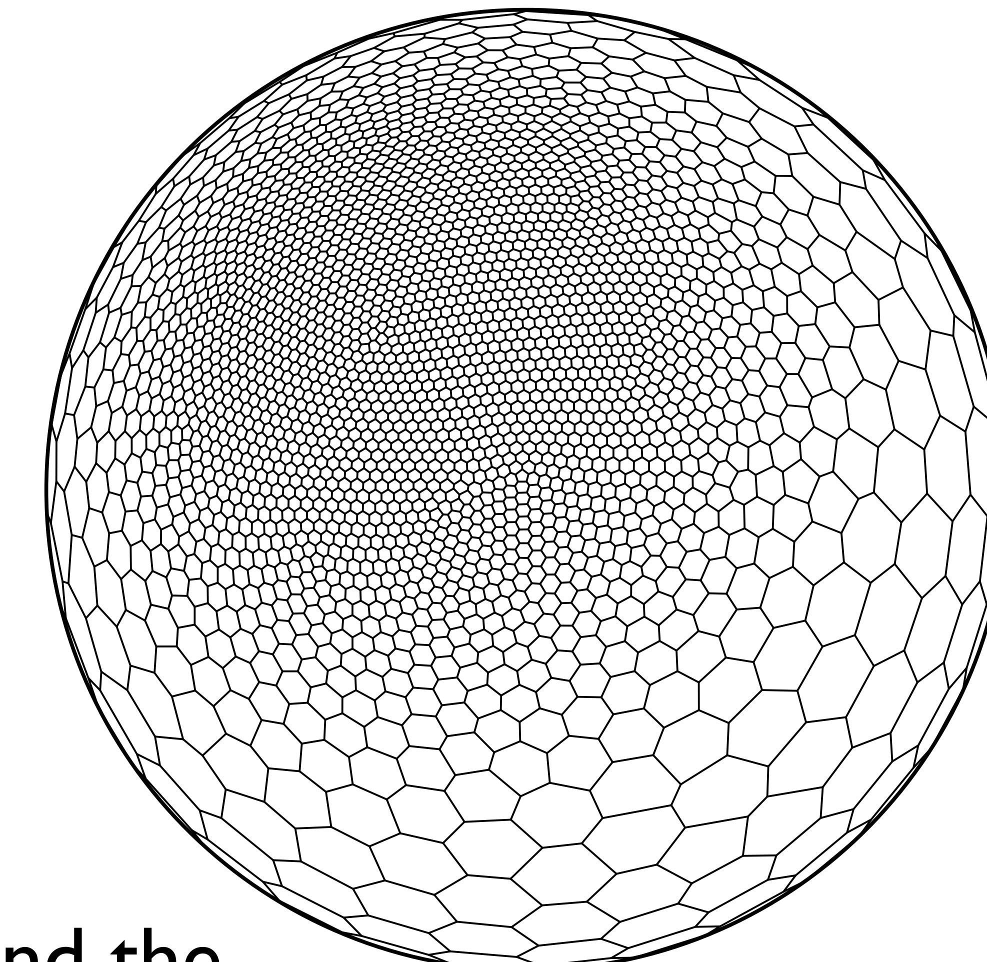
1. Relationship between mesh density function and resolution

$$\frac{h(\mathbf{x_i})}{h(\mathbf{x_j})} \approx \left(\frac{\rho(\mathbf{x_j})}{\rho(\mathbf{x_i})}\right)^{d+2}$$

d : dimension of space to tessellate

$h(\mathbf{x})$: nominal grid spacing

$\rho(\mathbf{x})$: user-defined density function

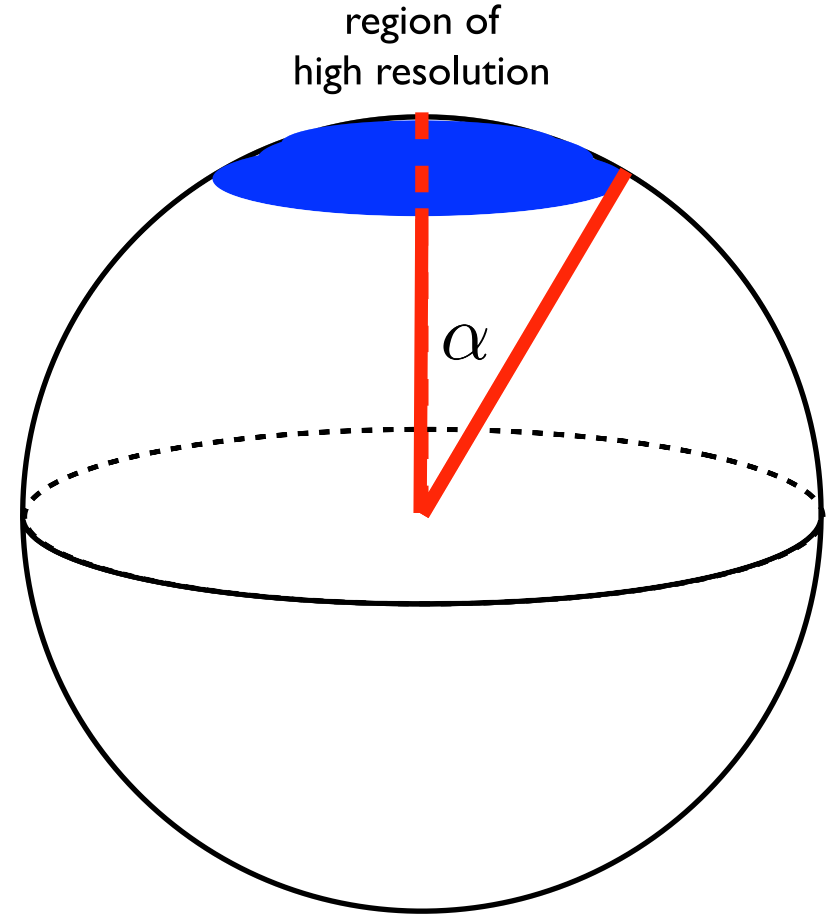


2. Mesh quality and polygon shape

The preferred polygon is the hexagon and the hexagons are guaranteed to get more uniform as we increase the number of generators with a fixed density function.

Tessellating big patches of the Earth at a fraction of the cost ....

$$N = \frac{8\pi}{\sqrt{3}}\left(\frac{R}{dx_f}\right)^2 \left[\underbrace{\sin^2\left(\frac{\alpha}{2}\right)}_{\text{high resolution}} + \underbrace{\frac{1}{\gamma^2}\left(1-\sin^2\left(\frac{\alpha}{2}\right)\right)}_{\text{low resolution}}\right]$$



N : total number of degrees of freedom

R : radius of sphere (km)

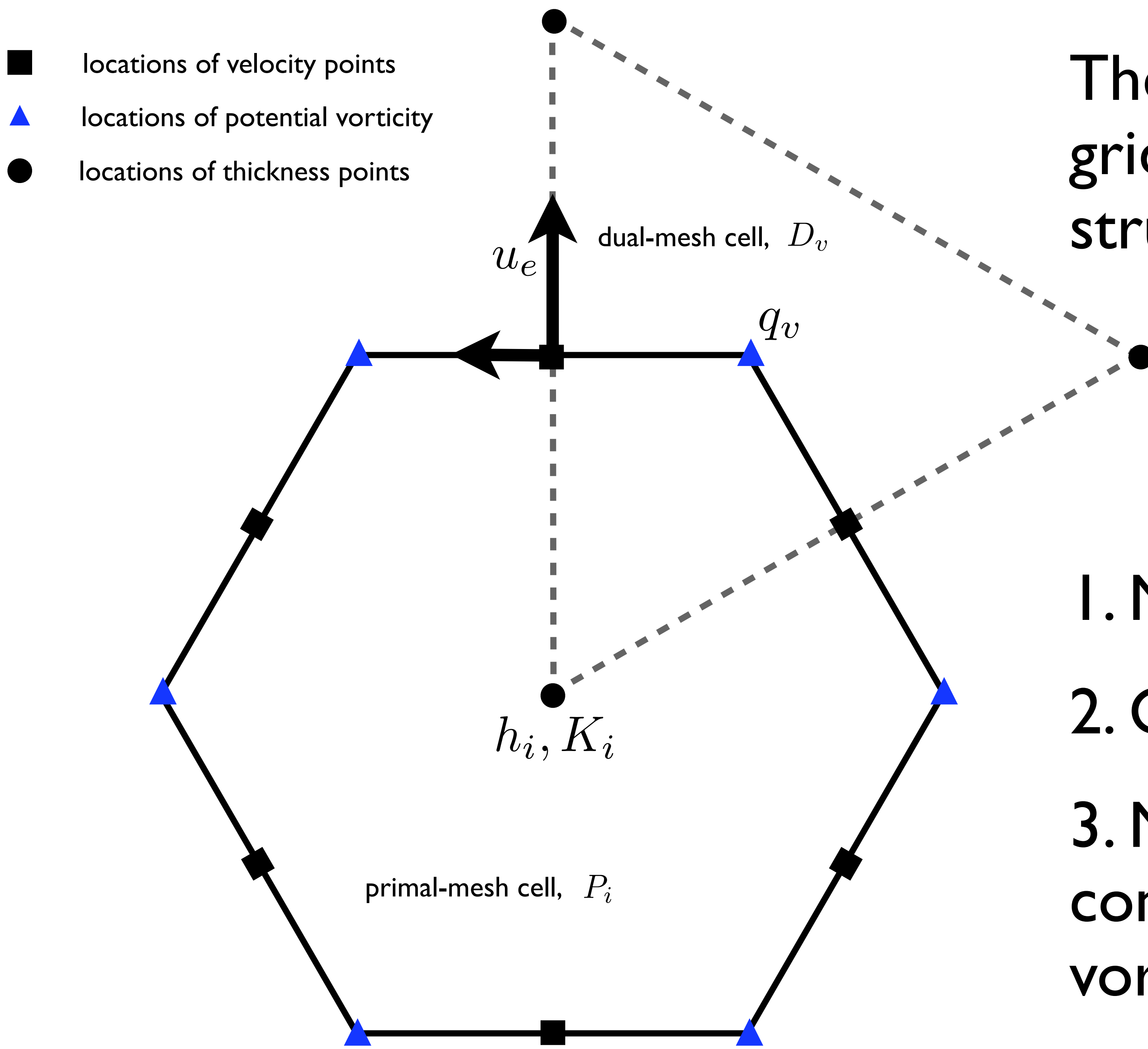
dx_f : grid spacing in high-res region (km)

α : angular width of high-res region (radians)

γ : low-res grid spacing / high-res grid spacing

For our typical applications we have γ=8 and α=40 degrees.
More than 90% of our degrees of freedom residing in our high-resolution region.

Now we have a mesh, but we still need a method!



The method is a finite-volume, C-grid discretization on arbitrarily structured polygons.

1. Maintains geostrophic balance.
2. Conserves energy.
3. Maintains Lagrangian conservation of potential vorticity.

Thuburn, J., Ringler, T., Skamarock, W., & Klemp, J. (2009). Numerical representation of geostrophic modes on arbitrarily structured C-grids. *Journal of Computational Physics*, *228*(22), 8321–8335.

Ringler, T., Thuburn, J., Klemp, J., & Skamarock, W. (2010). A unified approach to energy conservation and potential vorticity dynamics for arbitrarily-structured C-grids. *Journal of Computational Physics*, *229*(9), 3065–3090.

Global Ocean Model Results

Conceptually, how do we go about evaluating a global, multi-resolution ocean climate model?

1. Determine if it is a viable global, quasi-uniform ocean model!

2. While holding the maximum resolution fixed, determine if the multi-resolution configuration can reproduce certain aspects of its quasi-uniform counterpart.

3. While holding the computational resources fixed, determine if the multi-resolution configuration and produce a better climate than its quasi-uniform counterpart.

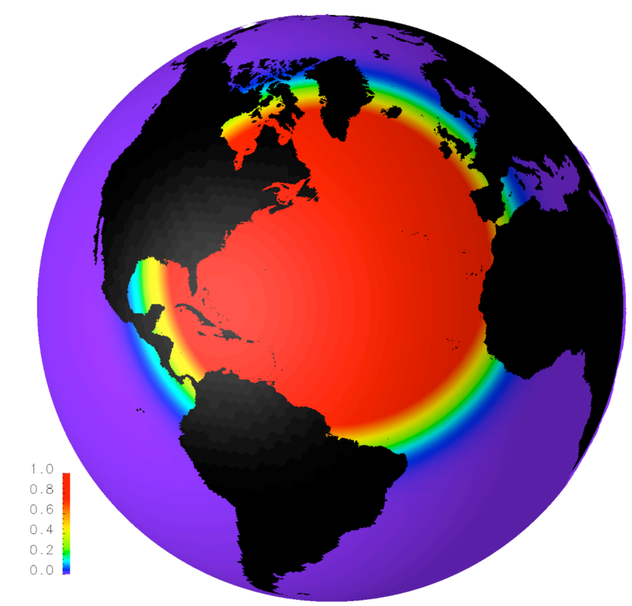
In practice, how do we go about evaluating a global, multi-resolution ocean climate model?

Model Simulations:

x1.15km: global, uniform-resolution of 15 km
x5.NA.15km: global, variable-resolution with 15 km in the North Atlantic
x5.NA.7.5km: global, variable-resolution with 7.5 km in the North Atlantic

Is the quasi-uniform model viable?
Compare x1.15km to observations.

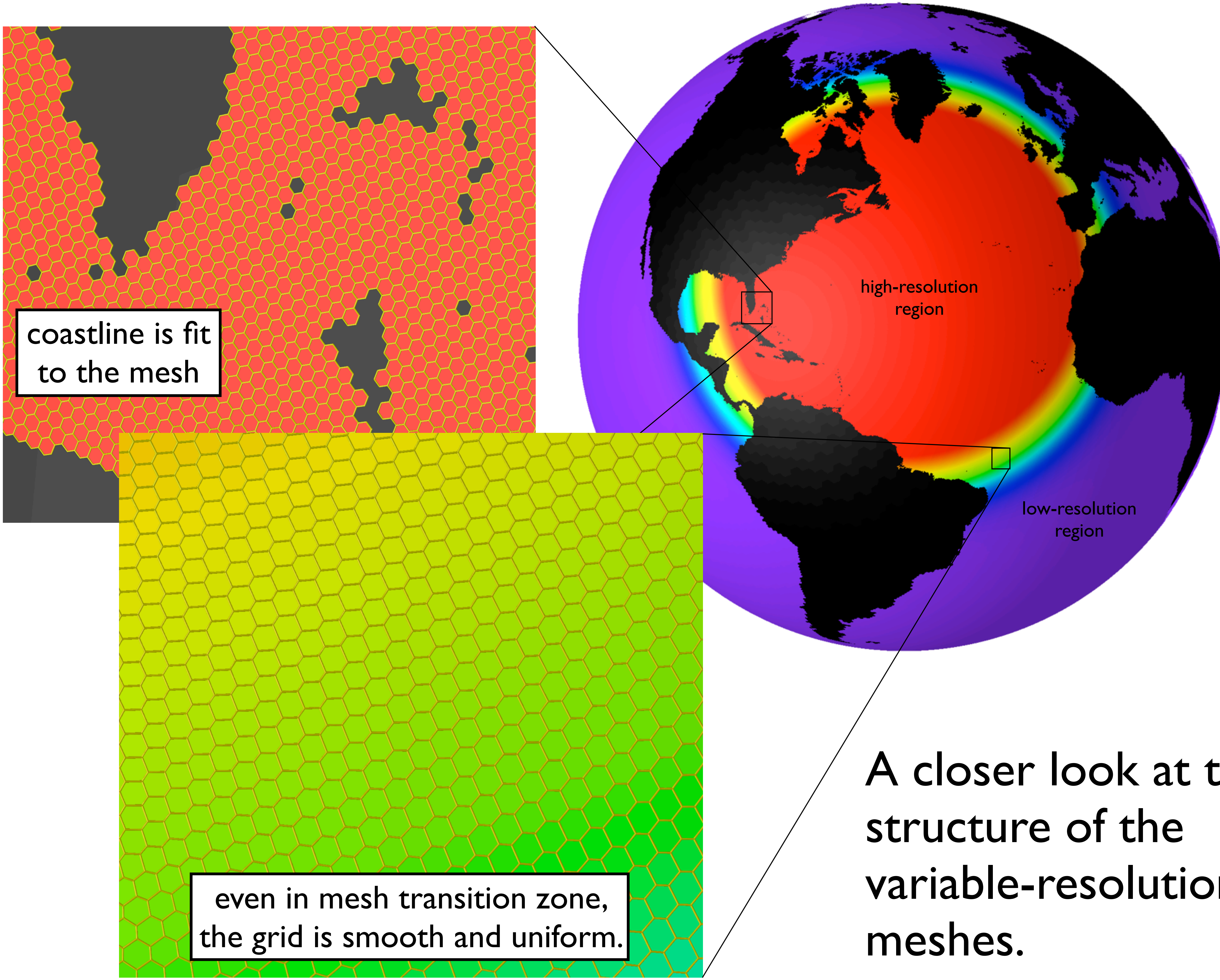
Is the multi-resolution viable at fixed resolution?
Compare x5.NA.15km to x1.15km in North Atlantic region.



Is the multi-resolution viable at fixed computation cost?
Compare x5.NA.7.5km to x1.15km in North Atlantic region.

Why these three simulations:

x1.15km: 1.8e6 cells, dt=600 s (~2 SYPD on 3000 procs)
x5.NA.15km: 2.5e5 cells, dt=600 s (1/7th cost of x1.15km)
x5.NA.7.5km: 1.0e6 cells, dt=360 s (same cost as x1.15km)



A closer look at the structure of the variable-resolution meshes.

Details of model configuration and forcing.

Duration: ~20 years. Analysis based on last 10 years.
Forcing: Monthly mean restoring to WOCE SST/SSS with 45 day time scale.
Forcing: Monthly mean normal-year wind stress forcing

Time stepping: Split-explicit with long/short time step of 600s/24s when using 15 km mesh.

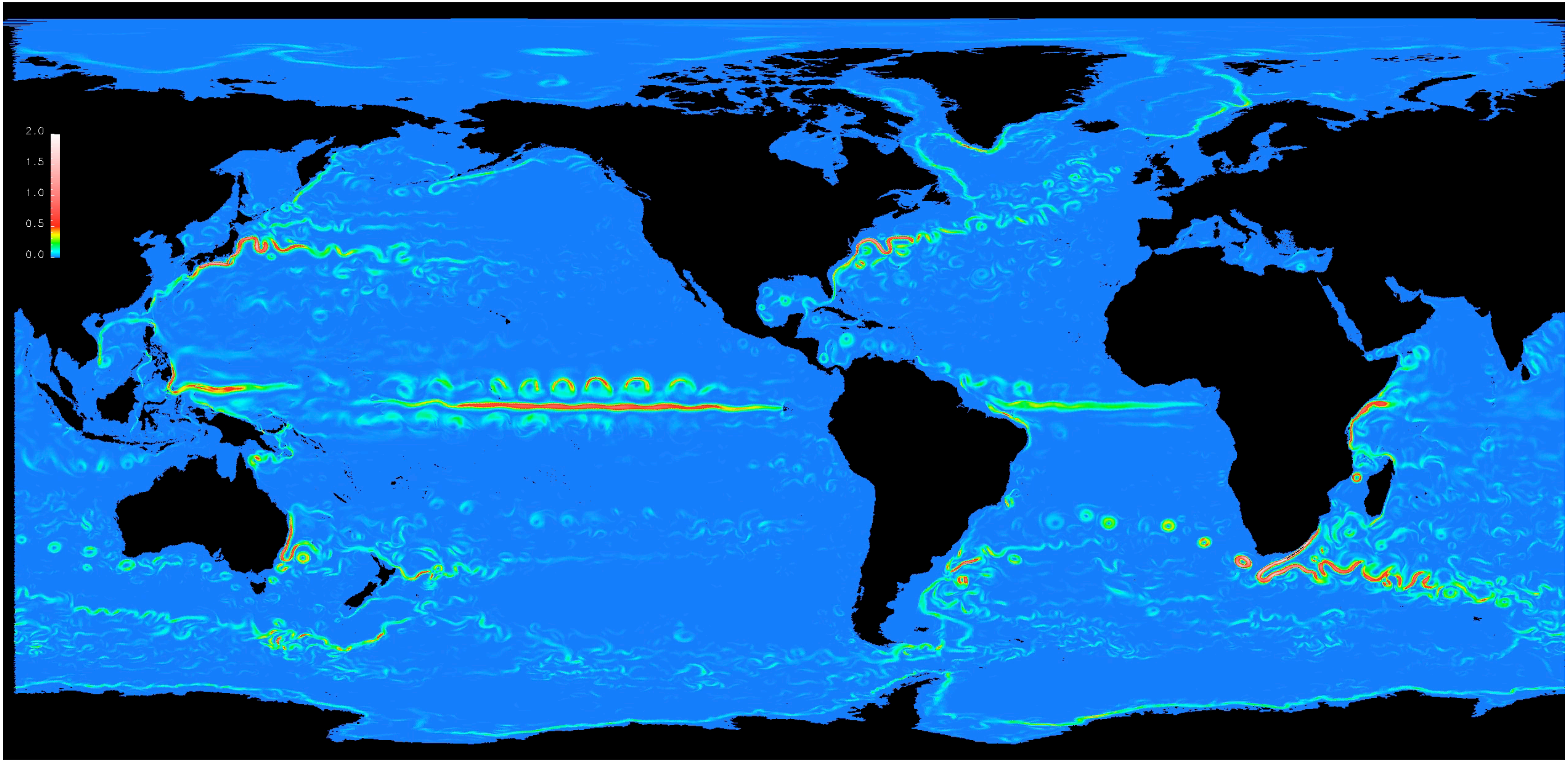
Vertical Discretization: z* with 40 vertical levels (no partial bottom cells)
Vertical Mixing: Solved implicitly with Pacanowski and Philander closure

Horizontal Discretization: C-grid on Voronoi-cell control volumes
Horizontal Mixing, Del4: biharmonic mixing on velocity as visc_0 * (dx/dx_0)^3
visc0 = 5.0e10 m4/s, dx_0 = 15 km
Horizontal Mixing, Del2: Leith enstrophy-cascade turbulence closure on velocity
(NOTE: No mesoscale eddy parameterization in used.)

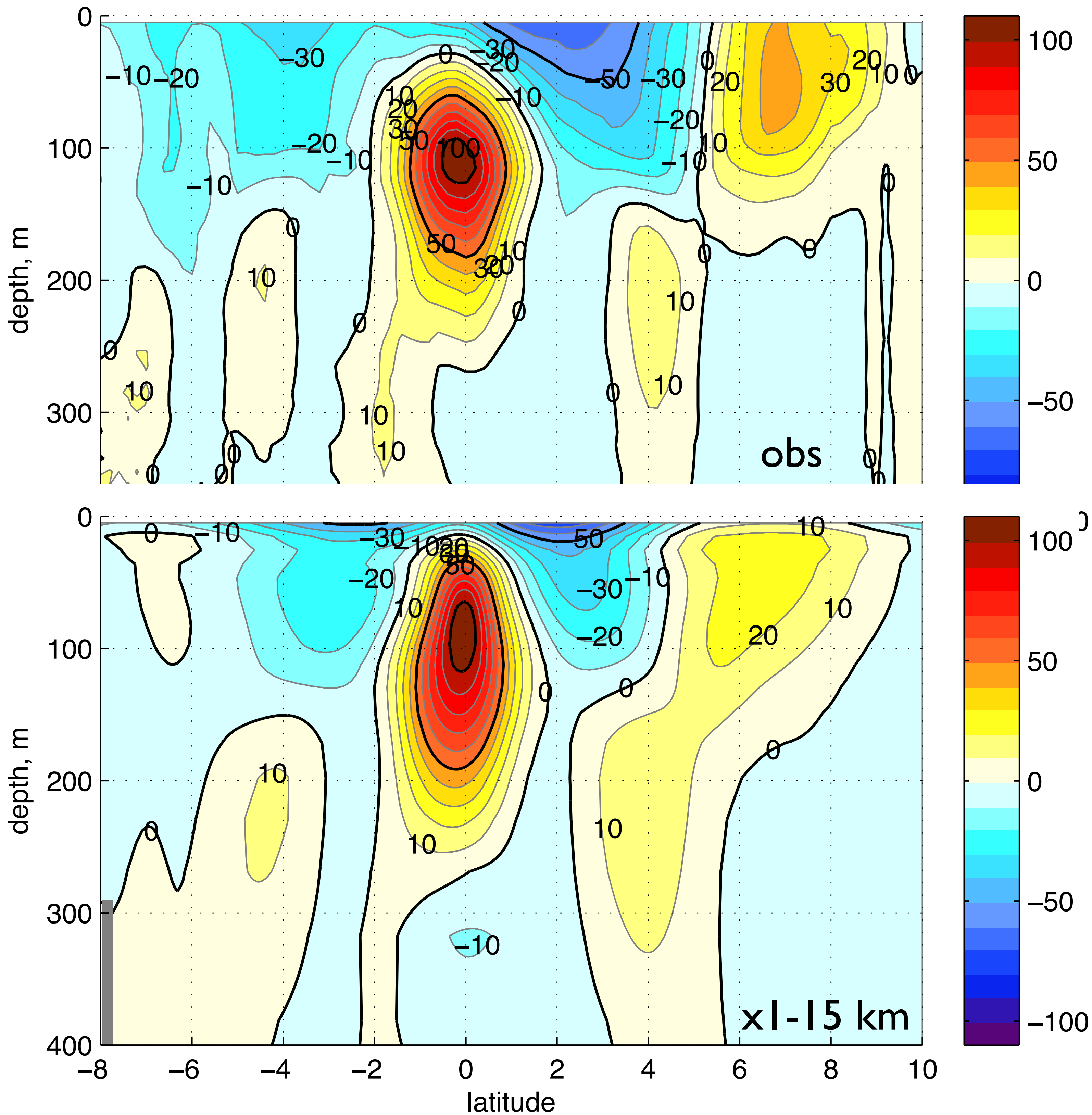
Transport: 3rd-order polynomial reconstruction with FCT, i.e. monotone transport.
(Tracers written in flux form with local conservation guaranteed.)

Same executable used for x1.15km, x5.NA.75km_15km and x5.NA.37.5km_7.5km simulations. The only difference between simulations is the horizontal mesh and time step.

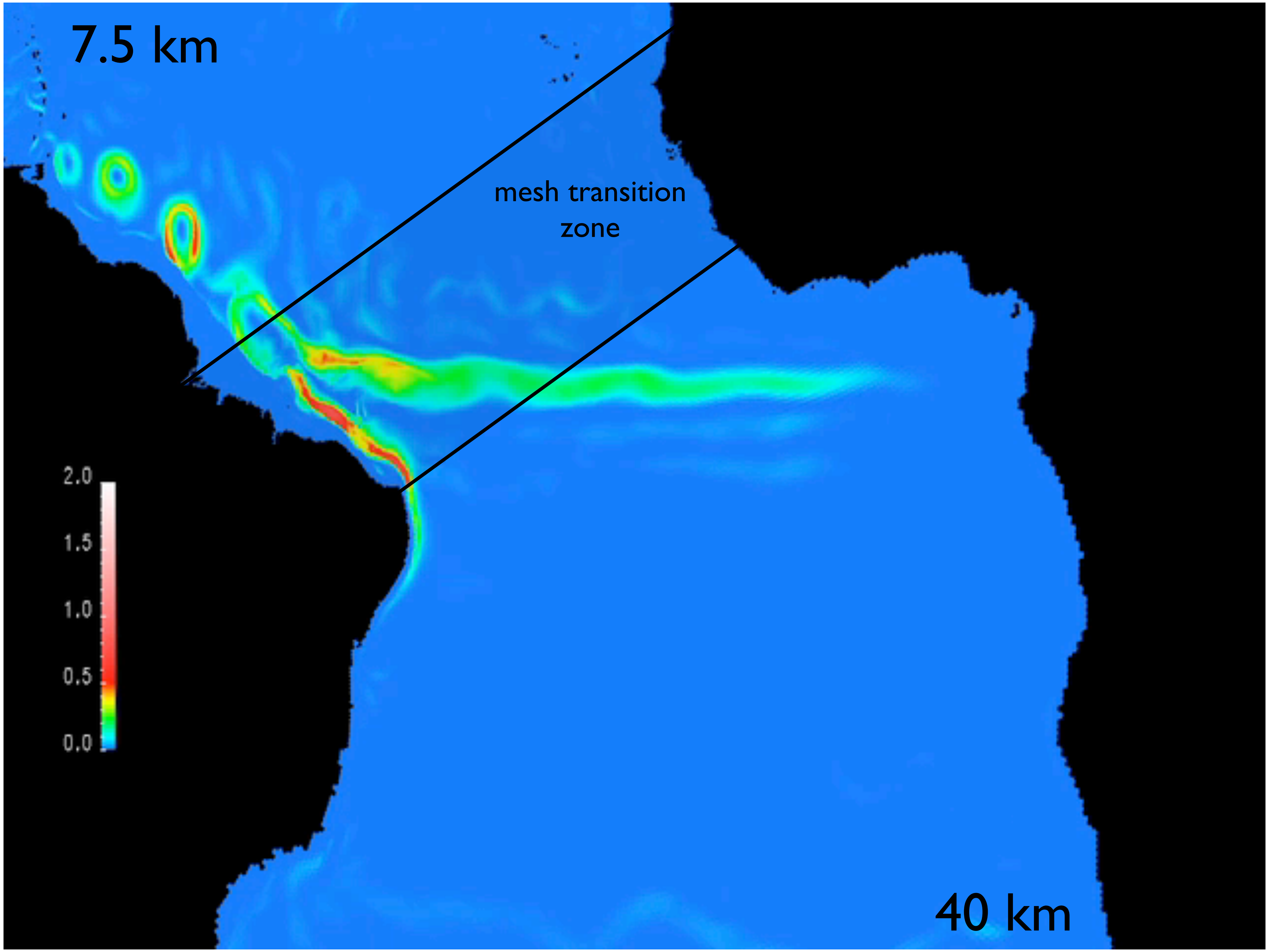
data: snapshots of KE @ 100 m depth
movie: one frame per month for 20 years



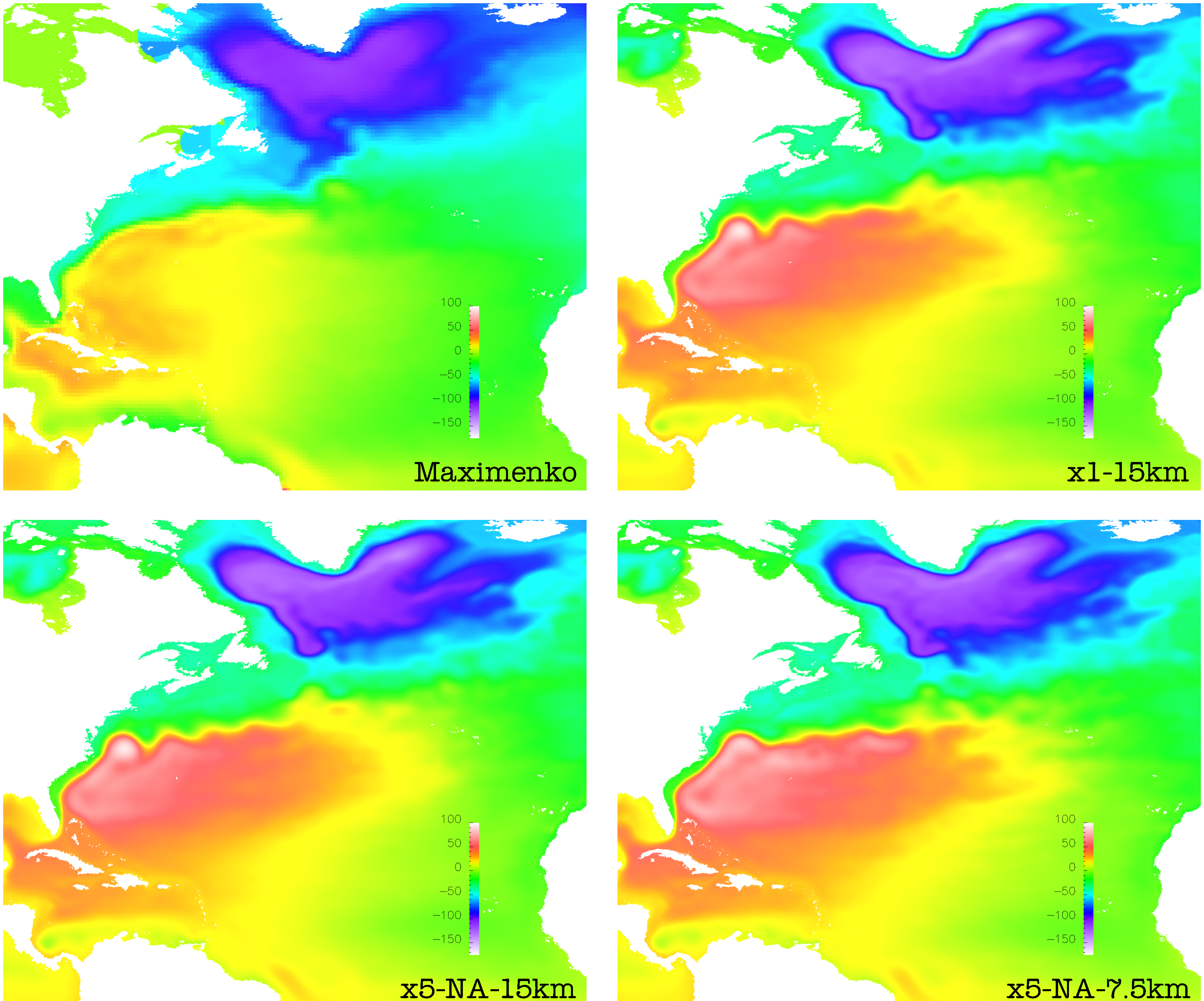
The equatorial currents are surprisingly accurate.



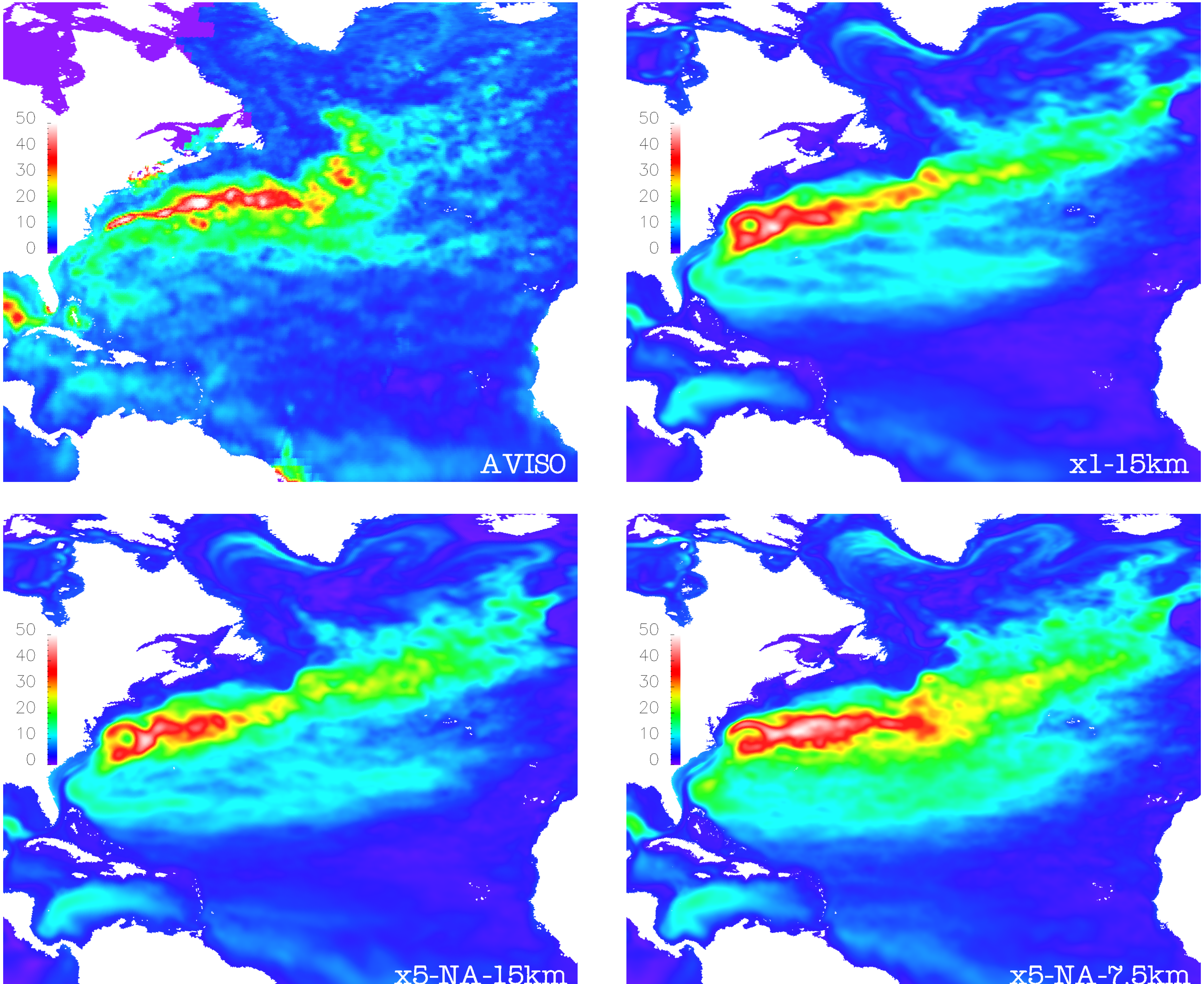
Retroflection of north Brazil current
data: snapshots of KE @ 100 m depth
movie: one frame per month for 20 years



Simulated SSH compared to observations

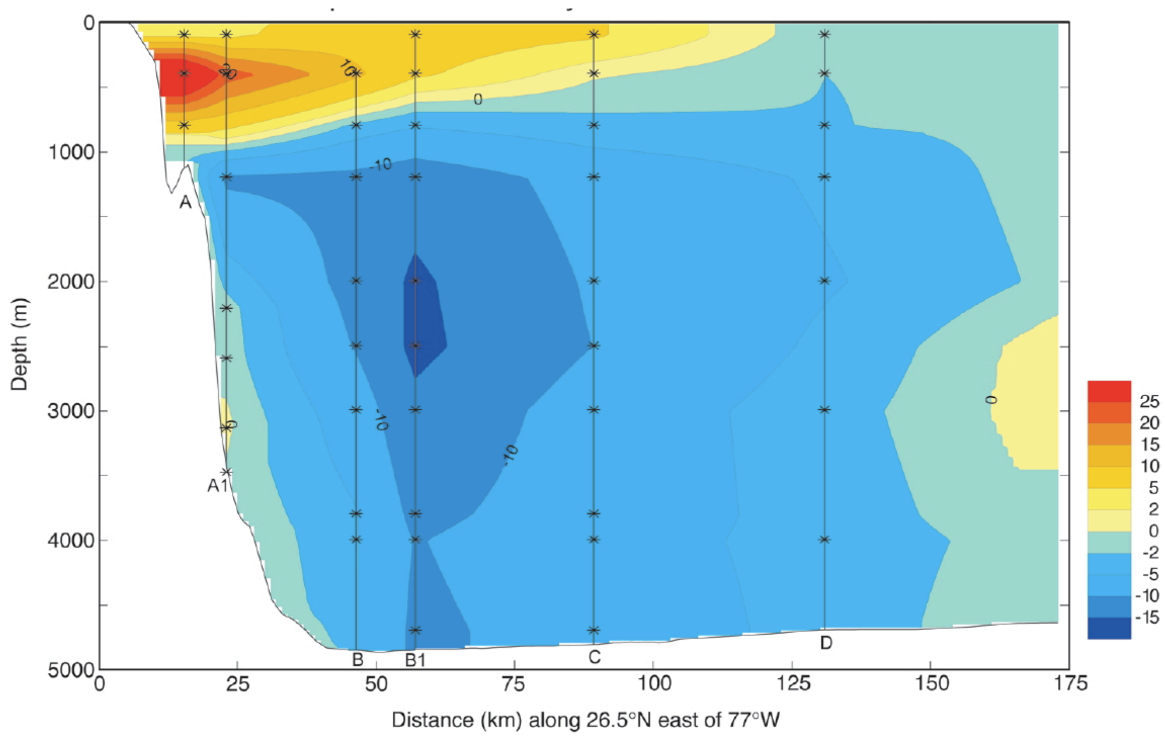


Simulated SSH variance compared to observations

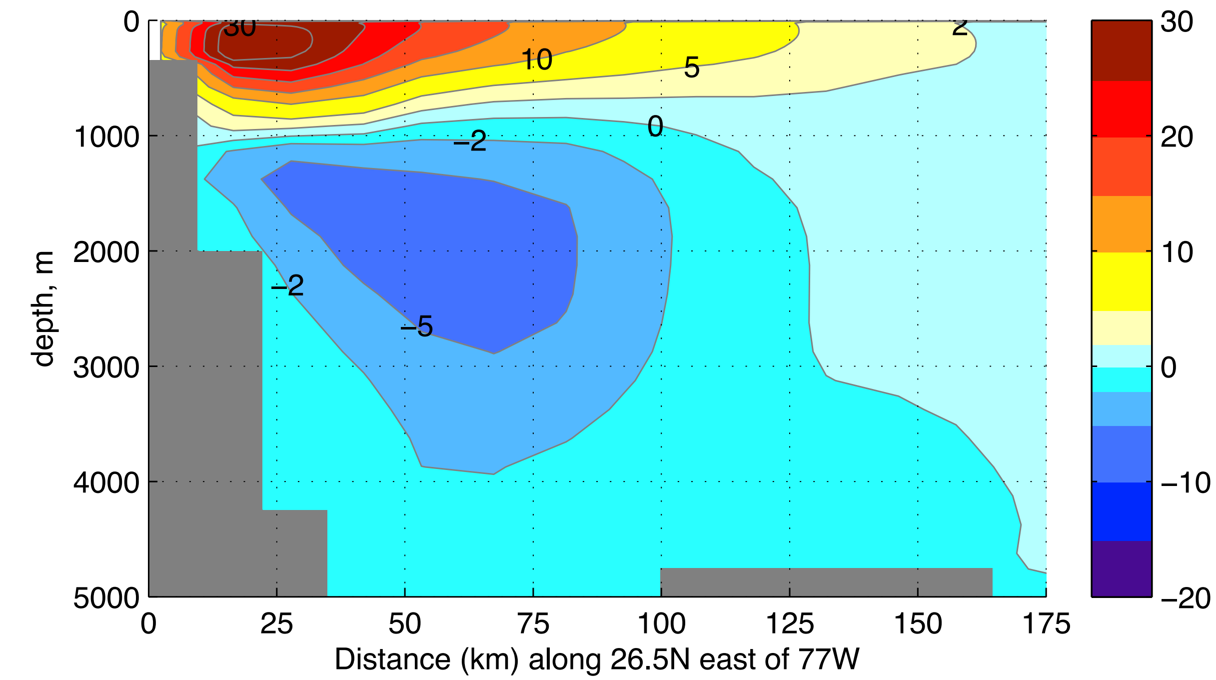


Deep Western Boundary Current

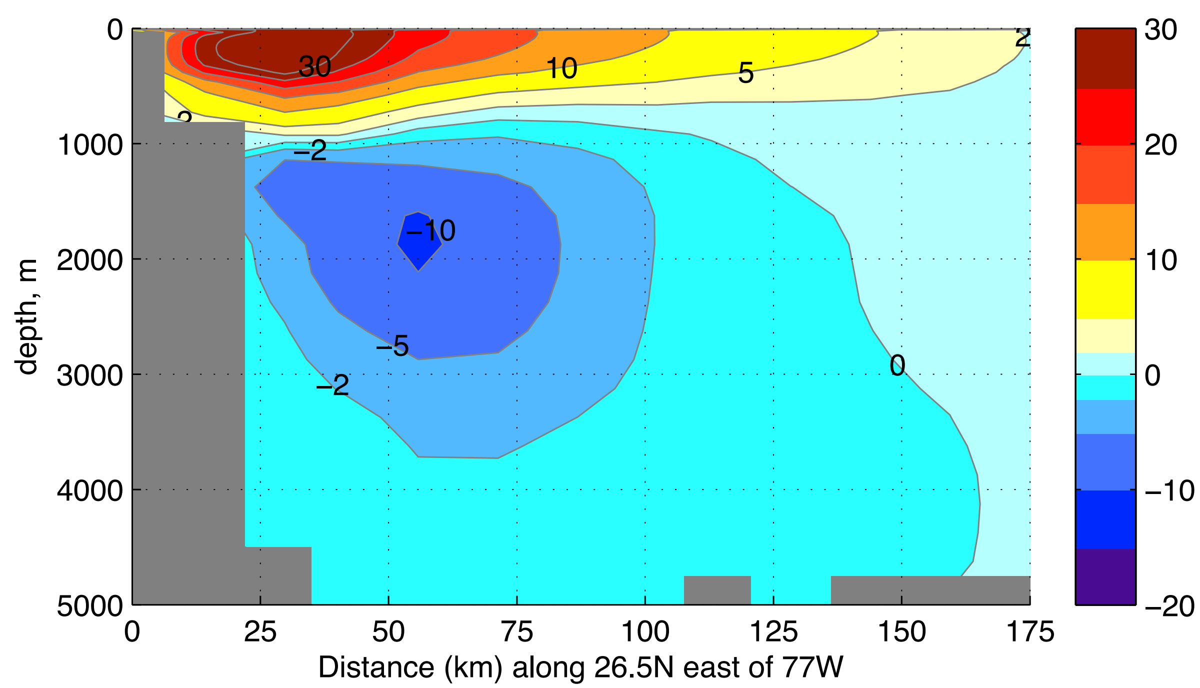
obs



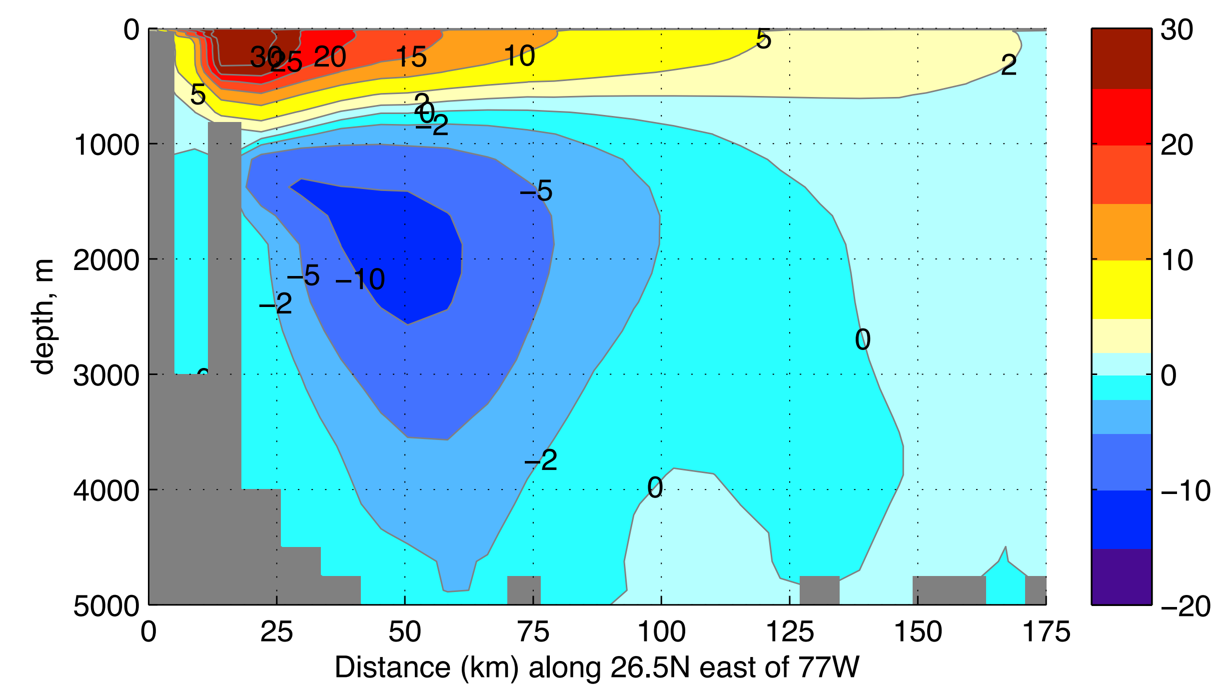
x1 NA 15 km



x5 NA 15 km



x5 NA 7.5 km



Revisiting the three questions ....

Q: Is the quasi-uniform model viable?
(Compare x1.15km to observations.)
A: The model is competitive with its peers, e.g. the x1.15km simulation is simulating equatorial currents and mesoscale activity slightly better than the POP 1/10 degree model.

Is the multi-resolution viable at fixed resolution?
(Compare x5.NA.15km to x1.15km in North Atlantic region.)
A: Unequivocally, yes. For all practical purposes the x5.NA.15km the is an exact reproduction of the x1.15km in the North Atlantic.

Q: Is the multi-resolution viable at fixed computation cost?
(Compare x5.NA.7.5km to x1.15km in North Atlantic region.)
A: Maybe. Certainly nothing got worse. Some aspect of the climate improved marginally.

These simulations form the basis of our first manuscript detailing the design of this multi-resolution ocean model.

https://www.dropbox.com/s/kqee4y7nlmapr7m/multiResolutionOcean.pdf

Global Atmosphere Model Results

(Same game, but a different system.)

Aqua-planet Simulations

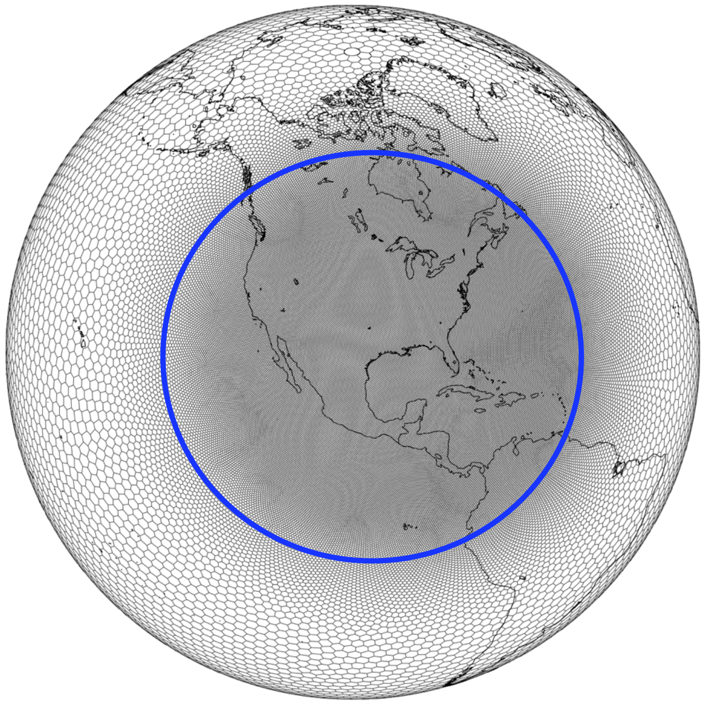
Resolution	Hyperdiffusion	Physics time step	Dynamics time step	Simulation Length (last 4.5 years analyzed)
10242 (~240km)	5e15	600 seconds	100 seconds	5 years
40962 (~120km)	5e14	600 seconds	100 seconds	5 years
163842 (~60km)	5e13	600 seconds	100 seconds	5 years
655362 (~30km)	5e12	600 seconds	100 seconds	5 years
65538 (~240km->30km)	Scaled by mesh density from 5e15 to 5e12	600 seconds	100 seconds	5 years

Why do aqua-planet simulations?

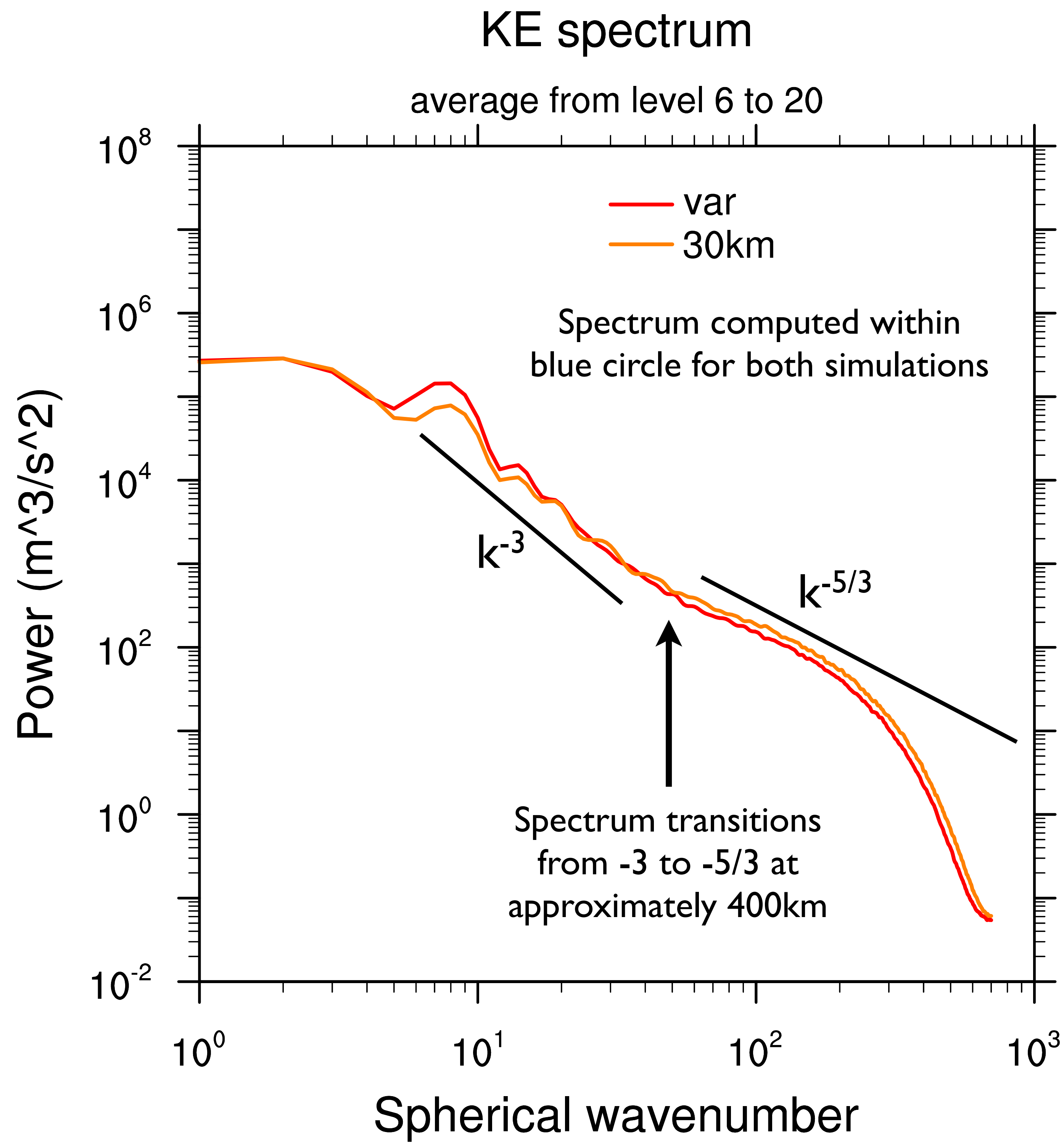
The forcing is zonally symmetric, so the climate should be zonally symmetric. Therefore, zonal asymmetry is error.

Transition to mesoscale regime is replicated in multi-resolution model.

30km to 240km mesh

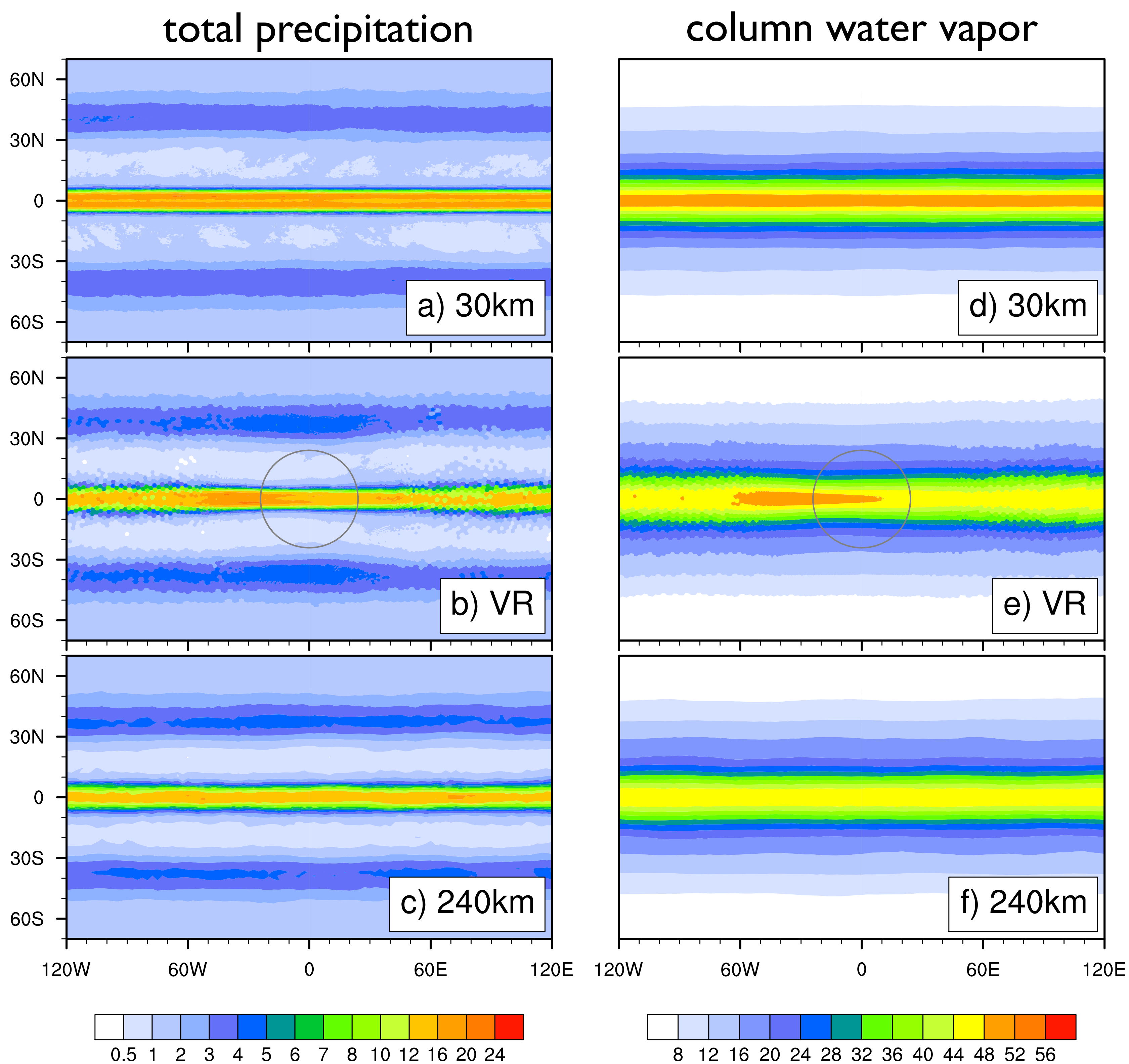


uniform 30km mesh

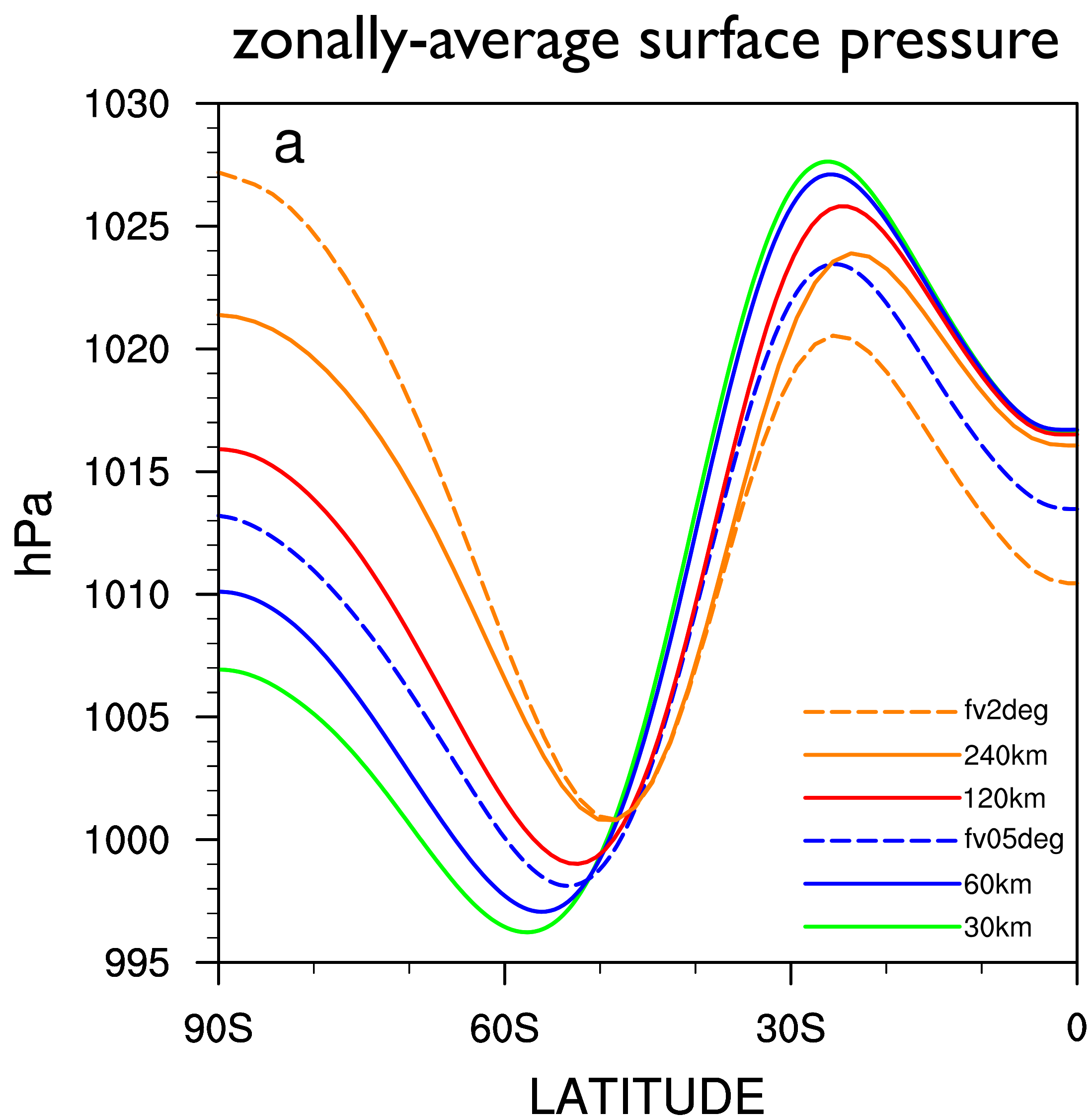


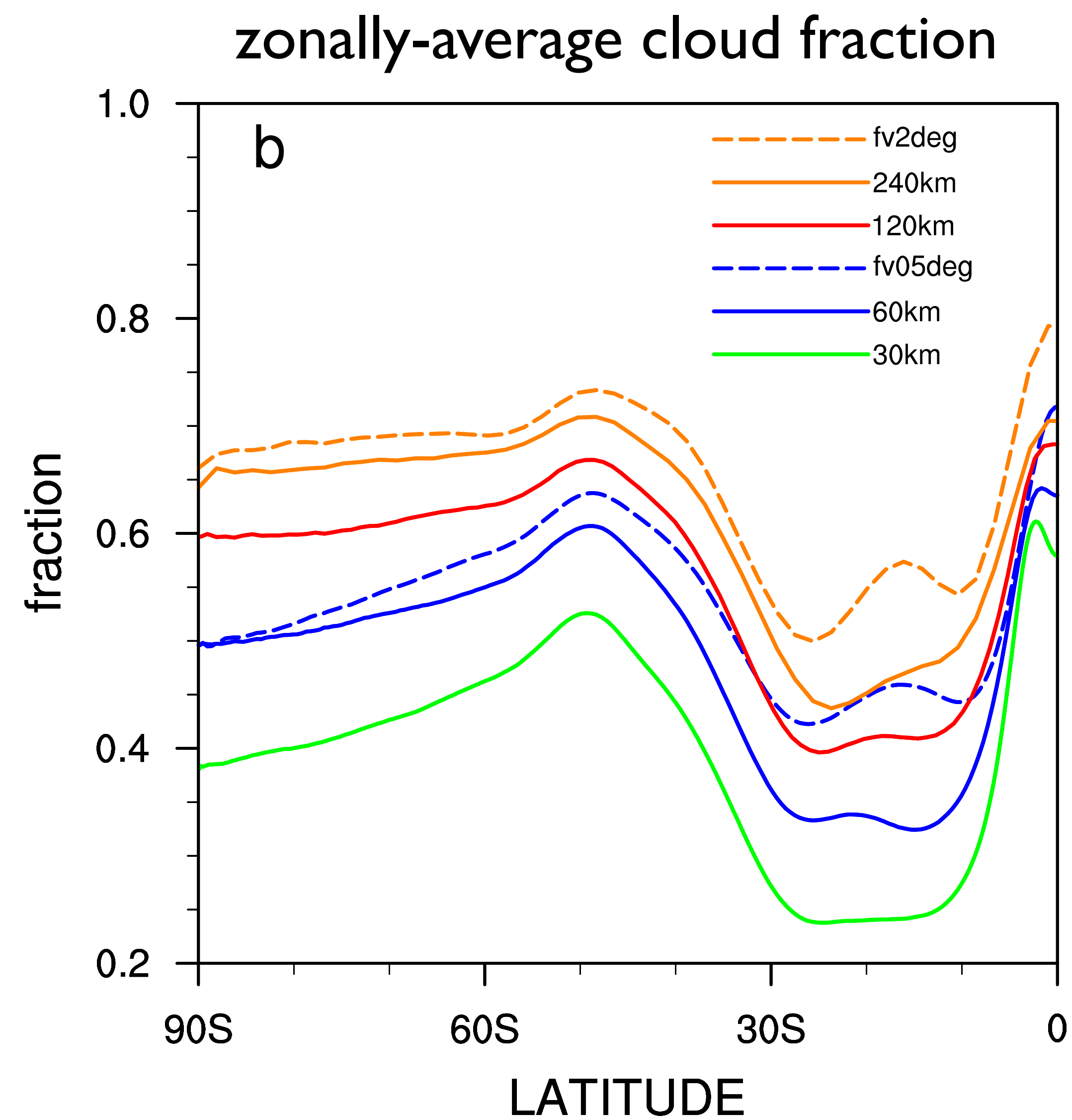
Full CAM4 physics using two meshes: a global 30km mesh and a variable 30km-240km mesh.
The energy spectra are, far all practical purposes, identical.

The picture is a bit more complicated in the atmosphere.



Is this really a problem with the multi-resolution approach?





The multi-resolution approach can only work if

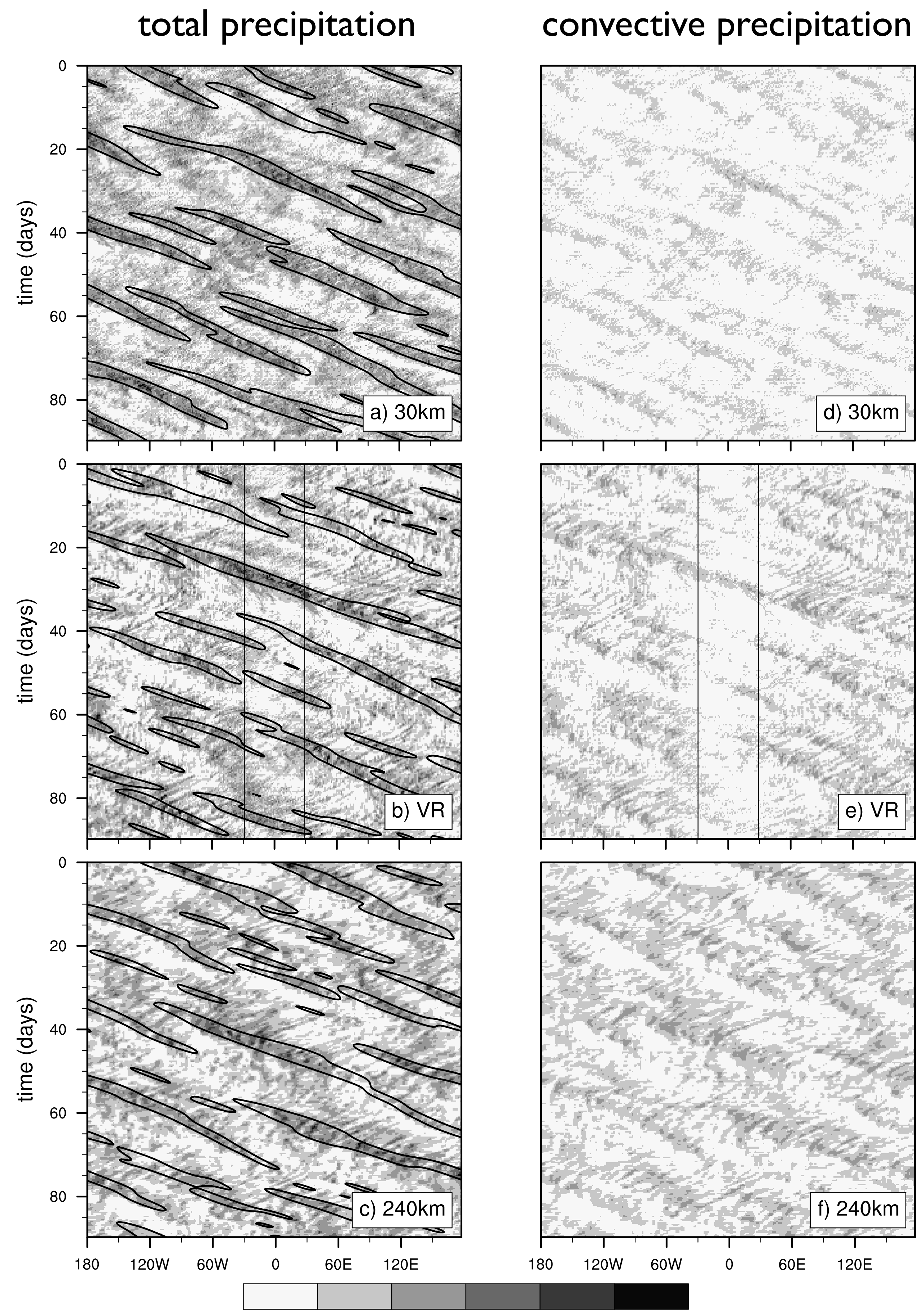
resolved+parameterized=constant

across a wide range of grid scales, i.e. we need "scale-aware physics".

It is not quite as bad as it seems.

Coherent tropical waves appear to move seamlessly through the mesh transition zone.

Yet, the partitioning of precipitation changes as resolution changes.



The aqua-planet simulations are published:

Rauscher, S., Ringler, T., Skamarock, W., & Mirin, A. A. (2012). Exploring a Global Multi-Resolution Modeling Approach Using Aquaplanet Simulations. *Journal of Climate*.

We are currently running a suite of AMIP simulations with these same meshes.

Why should we explore the multi-resolution approach to global climate modeling?

Why develop a multi-resolution capability #1: Study regional climate processes in a global modeling system

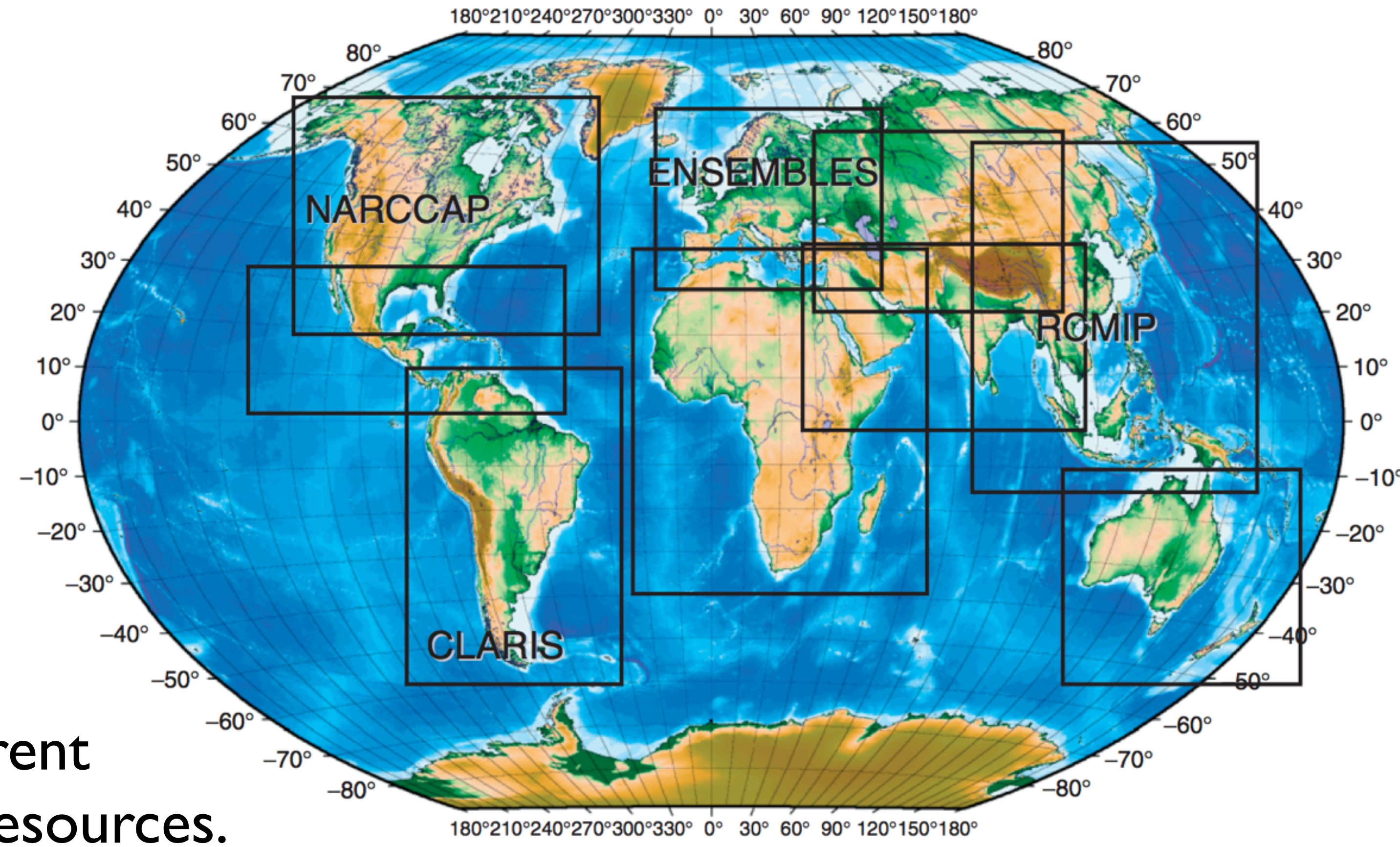
(without the need for an INCITE grant!)

The global modeling and regional modeling communities aspire to answer essentially the same question: How does the climate change with increasing levels of of GHGs?

The communities are differentiated primarily by the spatial/temporal scales that are accommodated.

The two communities have simply made different decisions on how to allocate computational resources.

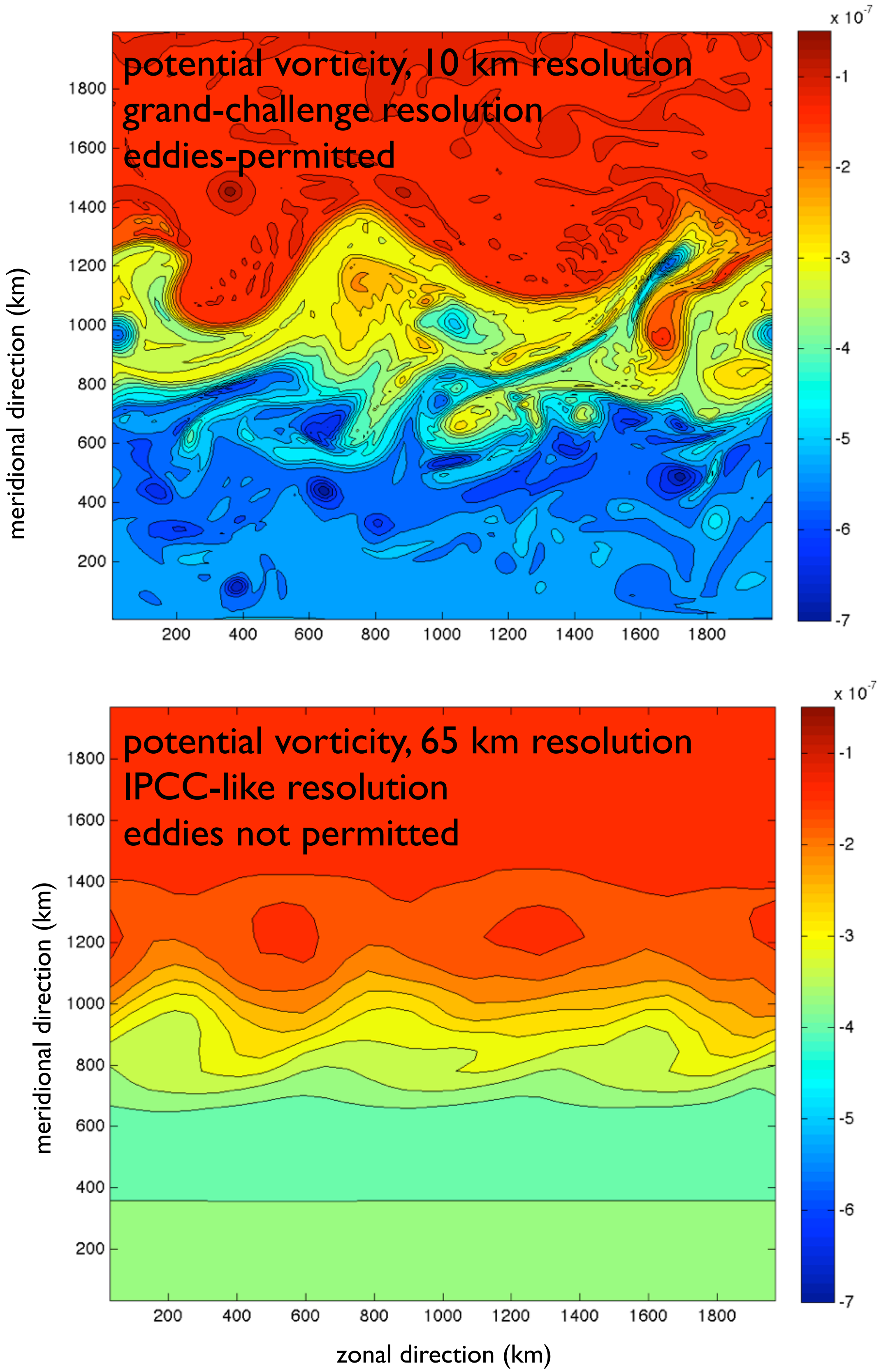
Typical Limited Area Domains[1]



A multi-resolution global modeling approach allows for the exploration of regional-scale climate processes at reasonable expense while maintaining a global modeling framework.

1. Rummukainen, M. (2010). State-of-the-art with regional climate models. *Wiley Interdisciplinary Reviews: Climate Change*, *1*(1), 82–96.

Why develop a multi-resolution capability #2: A route to more robust physical parameterizations



Ocean eddies are a key mechanism in the climate system for the poleward transport of heat. Thus eddies are parameterized in typical climate-change simulations.

In this case, we use the Gent-McWilliams parameterization where heat transport is a function of kappa (a user-defined parameter).

Unfortunately, kappa is a function of dx. A multi-resolution approach will 1) break scale-dependent parameterizations and 2) allow us to efficiently construct more robust, scale-aware parameterizations since multiply scales are included in a single simulation.

Low-hanging fruit, i.e. likely places to demonstrate value

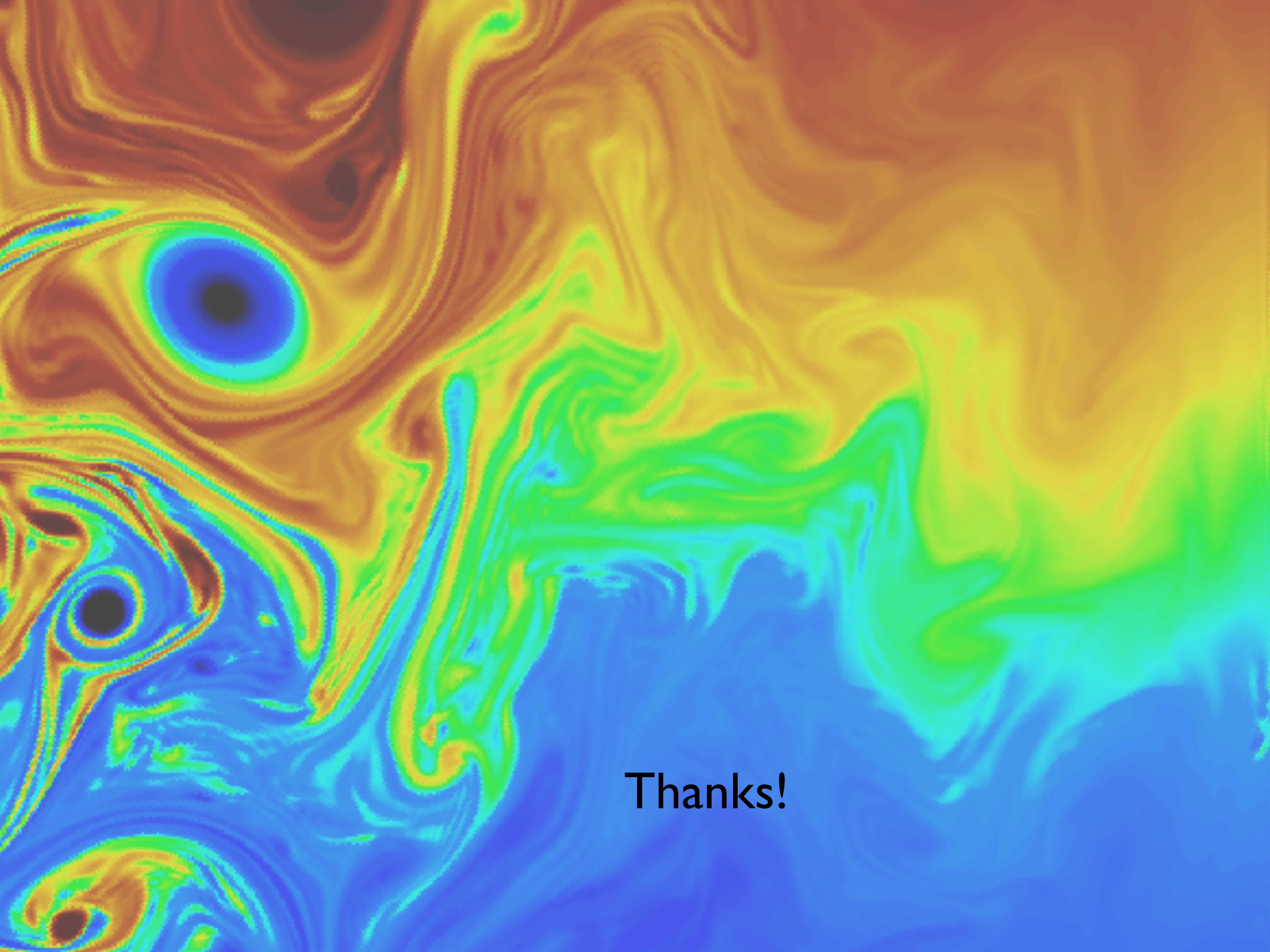
Places/Situations for "easy wins":

a. systems of relatively small areal extent
   1. Arctic (only 8% of surface area is poleward of 60N)
   2. Antarctic (only 12.5% of surface area is poleward of 45S)

b. systems with strong, regional feedback
   1. coupled ocean/atmosphere simulations in regions of stratocumulus
   2. hurricanes in, say, the tropical Atlantic

c. systems with strong boundary forcing
   1. ocean shelf overflow regions
   2. simulations of snow-pack in topographically-complex regions

d. processes linked to episodic events that benefit from enhanced resolution
   1. heat waves
   2. extreme precipitation events


Thanks!

Numerics:

Thuburn, J., Ringler, T., Skamarock, W., & Klemp, J. (2009). Numerical representation of geostrophic modes on arbitrarily structured C-grids. *Journal of Computational Physics*, *228*(22), 8321–8335.

Ringler, T., Thuburn, J., Klemp, J., & Skamarock, W. (2010). A unified approach to energy conservation and potential vorticity dynamics for arbitrarily-structured C-grids. *Journal of Computational Physics*, *229*(9), 3065–3090.

Grid Generation:

Ringler, T., Ju, L., & Gunzburger, M. (2008). A multiresolution method for climate system modeling: application of spherical centroidal Voronoi tessellations. *Ocean Dynamics*, *58*(5), 475–498.

Ju, L., Ringler, T., & Gunzburger, M. (2011). Voronoi Tessellations and their Application to Climate and Global Modeling. Numerical Techniques for Global Atmospheric Models, Springer Lecture Notes in Computational Science and Engineering, Eds. P. H. Lauritzen, C. Jablonowski, M. A. Taylor and R. D. Nair, 2011, 1–30.

Shallow-Water:

Ringler, T. D., Jacobsen, D., Gunzburger, M., Ju, L., Duda, M., & Skamarock, W. (2011). Exploring a Multiresolution Modeling Approach within the Shallow-Water Equations. *Monthly Weather Review*, *139*(11), 3348–3368. doi:10.1175/MWR-D-10-05049.1

Hydrostatic Atmosphere:

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Non-Hydrostatic Atmosphere:

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